Appendix 2.4 A1

Task 2.4 A1: TREATMENT AND REUSE OF AGRICULTURAL DRAINAGE WATERS

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LEGAL NOTICE

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for *Treatment and Reuse of Agricultural Drainage Waters*, which is a subcontract conducted by the University of California, Riverside for the project entitled *Electrotechnology Applications for Potable Water Production and Protection of the Environment*, Contract No. 500-97-044**,** managed by Southern California Edison. The report is entitled "Electrotechnology Applications for Potable Water Production and Protection of the Environment: Treatment and Reuse of Agricultural Drainage Waters." This project contributes to the Industrial/Agricultural/Water End-Use Energy Efficiency area.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index/html or contact the Commission's Publications Unit at 916-654-5200.

EXECUTIVE SUMMARY

The work presented in this report presents a preliminary evaluation of the efficacy of reclaiming agricultural drainage water generated in the Imperial Valley for irrigation reuse. It is hypothesized that a portion of Colorado River water currently used for irrigation in the Imperial Valley, approximately 10 percent or 300,000 acre-feet per year, could be exchanged for municipal purposes if agricultural drainage waters are reclaimed and reused for irrigation within the Imperial Valley.

Agricultural Drainage Water

Two important issues surrounding the efficacy of reclaiming agricultural drainage water generated in the Imperial Valley for irrigation reuse purposes within that region are: (1) agricultural drainage water flow volume and quality, and (2) water quality criteria for crop and soil conditions in the Imperial Valley.

Agriculture in the Imperial Valley relies on irrigation water from the Colorado River via the All American Canal. Based on the Colorado River Seven Party Agreement, the Imperial Irrigation District (IID) is entitled to 2.9 of the 4.4 million acre-feet per year entitlement to California. Of the 2.9 million acre-feet per year IID entitlement, about 2.6 million acre-feet per year are delivered to users within the district.

To prevent salinity buildup in the soil, irrigation water in excess of the consumption use demand of the crops must be applied to the fields. Excess irrigation water is referred to as *agricultural drainage water*. Agricultural drainage waters from the various fields are collected in a series of unlined drainage canals and drainage laterals that are analogous to a municipal storm or sanitary sewer system. These canals and laterals ultimately discharge into the Alamo River, the New River, or directly into the Salton Sea (Figure ES-1).

Approximately 850,000 acre-feet of agricultural drainage water flow into these two rivers. Nearly 100 percent of the Alamo River's average annual flow of 600,000 acre-feet is agricultural drainage. However, it is estimated that only 57 percent of the New River's average annual flow of 450,000 acre-feet is comprised of agricultural flow. A summary of inflows based on recent U.S. Geological Survey data is presented in Table ES-1.

Imperial Valley agricultural drainage water is brackish. The historical average TDS of the Alamo River is around 2,400 mg/L. In contrast, the average TDS of Colorado River water used for irrigation is about 800 mg/L. The agricultural drainage volume is approximately one third of the applied irrigation water. Assuming that there is no net accumulation of salt in the soil, the TDS of the resulting drainage water should be three times that of the applied water, which it is. Average historical water quality data for the Alamo River based on USGS measurements near Calipatria are summarized in Table ES-2.

Reuse Water Quality Criteria

Water quality criteria are important considerations in evaluating the efficacy of reclaiming agricultural drainage water for irrigation reuse purposes. Depending on the soil and crops under irrigation, these water quality criteria will vary considerably. The principal parameters of concern are salinity (EC), sodium and chloride concentrations, and the sodium absorption ratio (SAR). Based on a survey of the soil and crop types within the Imperial Valley, the following guidelines for acceptable water quality were developed and summarized in Table ES-3.

Reuse Alternatives

Two alternatives have been identified for consideration, both of which provide up to 300,000 acre-feet of reclaimed water from the Alamo River for agricultural irrigation reuse:

- Alternative A involves the reuse of agricultural drainage water with no desalinization treatment. Water would be extracted from the Alamo River near its mouth at the Salton Sea (Elevation = -227 ft MSL) and pumped back to Drop 1 of the All-American Canal (Elevation = ~150 ft MSL) or near the initial distribution point in the IID irrigation canal network (see Figure ES-1).

- Alternative B involves reuse of agricultural drainage water after treatment to reduce salinity by RO treatment (and necessary pretreatment processes to ensure effective RO treatment.) Treated water could be distributed more centrally to the treatment plant since this water will meet the suggested water quality criteria directly. Existing IID irrigation canals could be used for distribution; however, some type of conveyance system would be needed to carry the water to the initial distribution point(s).

Alternative A:

With respect to salinity, a schematic of the flow and salt mass load balance is shown in Figure ES-2 for Alternative A. As shown, it is proposed that up to 300,000 afy of Alamo River reuse water be blended with normal irrigation water from the Colorado River. At maximum reuse, the estimated salinity of the resultant irrigation water blend would be 1,050 mg/L (EC = 1.65), an increase of about 30 percent. Projected water quality for reuse rates of 0.1, 0.2, and 0.3 mafy is summarized in Table ES-4.

Alternative B:

Although increased salinity up to the projected levels for Alternative A should have little potential impact on relative crop yield in the Imperial Valley, there will be a reluctance to accept untreated water for reuse, especially if there is no economic incentive. Therefore, for Alternative B it is proposed that a RO treatment system be developed to generate a reclaimed water flow, up to 300,000 afy, which is similar in salinity level to that of the existing

Colorado River water (EC = 1.2 dS/m). Reuse water would be first be extracted from the Alamo River and conveyed to a treatment site adjacent to the Alamo River near the Salton Sea. Treated water could be conveyed to any location in the IID irrigation canal system for distribution.

A schematic of the flow and salt mass load balance is shown in Figure ES-3 for Alternative B. A conceptual diagram of the treatment plant for Alternative B is shown in Figure ES-4. Because of the low salinity water produced by RO treatment only 210,000 afy would need to be treated by RO. The final product water, 300,000 afy with an EC = 1.2 dS/m, will be produced by blending 90,000 afy of bypassed agricultural drainage water.

Bench-Scale Pilot Testing – Alternative B

Bench-scale testing was conducted to obtain preliminary data regarding the technical feasibility of desalinating agricultural drainage water by RO treatment as proposed in Alternative B.

Because RO membranes are subject to scaling and fouling, which adversely affects their long-term performance, pretreatment of agricultural drainage water is required to minimize the rate of scaling and/or fouling that may occur in the RO system. Thus, bench-scale testing for this study consisted of two aspects, pretreatment and RO desalination.

Three different pretreatment approaches were considered: (1) conventional treatment (sequential coagulation, flocculation, sedimentation, and granular-medium filtration), (2) softening (sequential lime-soda ash softening, sedimentation, and granular-medium filtration, and (3) membrane filtration (microfiltration (MF) and ultrafiltration (UF)). Effectiveness of the pretreatment schemes was based on turbidity, pH, suspended solids (TSS), silt density index (SDI), and particle size analysis.

Effluent waters from the three different pretreatment schemes were tested with two different RO membranes in a recirculating flow flat-sheet membrane apparatus. Desalination effectiveness in terms of electroconductivity (EC) and total dissolved solids (TDS) was assessed. In addition, to qualitatively assess the effectiveness of the three different pretreatment schemes to minimize scaling and fouling, the RO membranes were examined by scanning electron microscopy (SEM) for scaling and fouling at the surface.

Water for the bench-scale study was obtained from the U.S. Geological Survey flow gage station, Station Number 10254670, on the Alamo River at Drop 3 near Calipatria, CA. Large samples, 350-370 gallons, were collected on a regular basis in 55-gallon drums and transported to the University of California, Riverside (UCR) Environmental Engineering Laboratory for the bench-scale tests. A summary of the collected Alamo River water quality is given in Table ES-5.

Pretreatment – Conventional Water Treatment

Conventional treatment processes were defined to include coagulation, flocculation, sedimentation, and granular medium filtration (a standard water treatment process train). Two standard water treatment coagulants, alum and ferric chloride, were evaluated. To determine optimum coagulant doses and flocculation velocity gradients, a series of jar tests were performed. Both alum and ferric chloride were found to be effective coagulants. Optimum doses were 30 mg/L for alum, and 20 mg/L for ferric chloride. Optimum velocity gradient, G, for both coagulants was found to be 40 s^{-1}.

The bench-scale conventional water treatment system consisting of an integrated chemical mixing chamber, three-stage flocculator, inclined-plate sedimentation tank, and dual-media filters was used to treat the collected Alamo River samples. Both alum and ferric chloride were tested. Average effluent characteristics of conventionally treated water are summarized in Table ES-6.

Based on the data collected, conventional water treatment produced water that was of sufficient quality for RO feed and desalination. Alum and ferric chloride were both found to be effective coagulants. Turbidity values for both coagulants were less than 1.0 NTU and the SDI values were found to be less than 5.

Pretreatment –Softening Water Treatment

Based on the composition of the Alamo River water, the most likely precipitates to form significant scale in RO units are calcium carbonate (calcite) and calcium sulfate (gypsite). The potential to form precipitates is based on solubility products and concentrations of the relevant species – calcium, carbonate, and sulfate.

Based on the characteristics of the Alamo River obtained in this study, the Langelier Saturation Index (LSI) at pH 8 is 1.0 for the projected RO feed water and 1.8 for the projected RO reject stream, indicating calcium carbonate scale potential. Further, at the projected concentrations for the RO reject stream, the calcium and sulfate concentrations are over the saturation product. Gypsite scale may therefore occur. To ensure that gypsite does not form, calcium removal and/or the use of complexing agents such as ethylenediamine tetraacetic acid (EDTA) or nitrilotriacetic acid (NTA) may be considered. In this study, the use of a conventional softening process, selective calcium lime-soda ash softening, was investigated. Selective calcium softening only removes calcium hardness; magnesium hardness is not removed. Based on theoretical calculations, it was estimated that 45 percent removal of calcium would be sufficient to prevent gypsite formation.

Softening treatment processes were defined to include selective calcium softening with ferric chloride coagulation, flocculation, sedimentation, and granular medium filtration. Stoichiometric additions of lime and soda ash, 175 mg/L and 240 mg/L, respectively, were used in both jar tests and continuous-flow testing. To determine optimum ferric chloride coagulant doses and flocculation velocity gradients, a series of jar tests were performed. Optimum ferric chloride doses were found to be 20 mg/L. Optimum velocity gradient, G, was found to be 60 s^{-1}. Average effluent characteristics of Alamo River water treated by the continuous-flow softening process are summarized in Table ES-7.

Based on the data collected, Alamo River water treated by selective calcium lime-soda ash softening will produce water that is of sufficient quality for RO feed and desalination. Turbidity was less than 1.0 NTU and the SDI was found to be less than 5.

On the basis of both jar tests and continuous-flow bench testing, calcium hardness in excess of 45 percent can be achieved readily, minimizing gypsite formation potential in the RO reject stream. An average calcium hardness reduction of 55 percent was achieved in the bench-scale tests.

Pretreatment – Membrane Filtration (Micro/Ultrafiltration)

Microfiltration (MF) and ultrafiltration (UF) were investigated as an alternative to conventional treatment processes for pretreatment of Alamo River water prior to desalination using RO. The evaluation was carried out using both a stirred-cell UF apparatus and a bench-scale continuous flow membrane filter apparatus for MF. The goals were to evaluate the effects of transmembrane pressure (TMP) on filtrate flux for two flat sheet UF membranes and two different hollow fiber MF modules. Two feed waters, raw and settled-raw Alamo River water, were evaluated. Filtrate water quality was analyzed for total suspended solids (TSS), turbidity (NTU), silt density index (SDI), and particle size distribution analysis (PSD). Evaluation of long-term membrane degradation and fouling was not part of this study. Average influent and effluent concentrations for the CFMF study are presented in Table ES-8.

Both conventional and microfiltration treatments were found to be effective pretreatment for subsequent desalination using RO with virtually equal average removal efficiencies. However, greater variability of effluent water quality parameters was exhibited in the treated effluent from the conventional treatment, which may affect the long-term performance of downstream RO treatment.

Reverse Osmosis

Reverse osmosis was assessed as a means to reduce the salinity in Alamo River water, and to evaluate the efficacy of alternative pretreatment methods. A bench-scale continuous flow test-cell for flat-sheet membranes was used to determine the permeate flux of RO membranes at different TMP's, and to assess membrane desalination efficiency. Feed solutions were obtained from CFMF and conventional treatment with dual media filtration.

Clean water flux and permeate flux from feed water obtained from continuous microfiltration (CFMF) and from conventional treatment with dual media filtration (DMF) are reported in Table ES-9.

Permeate flux was linear for all TMP's investigated, and approximately one half of the clean water flux. There was little or no difference between the two membranes in terms of salt rejection. Major cation removal was 99 percent with sodium removal somewhat less at 95 percent.

Conclusions

The technical feasibility for treating and desalinating Alamo River water for reuse purposes has been demonstrated. Both conventional and microfiltration treatments produce suitable feed for downstream desalination by low pressure RO treatment.

- Nearly 100 percent of the Alamo River's average annual flow of 600,000 acre-feet is agricultural drainage, while only 57 percent of the New River's average annual flow of 450,000 acre-feet is comprised of agricultural flow.

- Imperial Valley agricultural drainage water is brackish. The measured average TDS of the Alamo River is around 2,400 mg/L. The average TDS of Colorado River water used for irrigation is about 820 mg/L. The principal parameters of concern are salinity, sodium and chloride concentrations, and sodium absorption ratio.

- On the premise that agricultural drainage water reuse will not affect crop yields significantly or decrease crop value per acre two water reuse alternatives were formulated:

  Alternative A was developed on the basis of the Alamo River water quality and blending requirements to meet the minimum reuse water quality criteria without treatment, and

  Alternative B was forwarded on the basis of the Alamo River water quality and the treatment requirements needed to ensure that the delivered reclaimed irrigation water was similar in quality to that of the Colorado River.

- Conventional water treatment and microfiltration can produce water that is of sufficient quality for RO feed and desalination, e.g. turbidity values less than 1.0 NTU and the SDI values less than 5.

- RO treatment can produce approximately 99 percent removal of major cations and approximately 95 percent removal of sodium.

Table ES-1. Average Annual Flows into the Salton Sea

River	Average annual flow, acre-feet/yr
Alamo River	600,000
New River	450,000
Whitewater River	60,000
Direct drainage	190,000
Miscellaneous	30,000
TOTAL INFLOW	1,330,000

Table ES-2. Alamo River Water Quality Characteristics[1]

Parameter	Units	Average
PH	pH units	8.0
Temperature	^oC	22
Electroconductivity (EC)	dS/m	3.5
Total suspended solids (TSS)	mg/L	560
Total dissolved solids (TDS)	mg/L	2,400
Turbidity	NTU	127
Alkalinity	meq/L	4.5
Hardness	meq/L	17.0
Calcium	mg/L	180
Magnesium	mg/L	97
Sodium	mg/L	460
Potassium	mg/L	11
Barium	mg/L	0.11
Iron	mg/L	0.026
Strontium	mg/L	3.2
Selenium	mg/L	0.007
Chloride	mg/L	540
Sulfate	mg/L	830
Fluoride	mg/L	0.58
Boron	mg/L	0.71
Silica	mg/L	12
TKN	mg/L	2.6
Ammonia nitrogen (as N)	mg/L	1.1
Nitrite + Nitrate nitrogen (as N)	mg/L	7.4
Phosphorus-ortho	mg/L	0.38

[1] Alexander, R.B., Slack, J.R., Ludtke, A.S., Fitzgerald, K.K. and Schertz, T.L. Data from Selected U.S. Geological Survey National Stream Water-Quality Monitoring Networks (WQN) USGS Digital Data Series DDS-37, Station 10254670 Alamo River at Drop 3 near Calipatria CA.

Table ES- 3. Water Quality Criteria Guidelines for Irrigation in the Imperial Valley

Parameter	Units	Limit	Restriction
Salinity	dS/m	2.5	Higher salinity may result in greater than 10% reduction in relative crop yield
Sodium	meq/L	20 (5)	Sodium toxicity (Leaf damage through spray irrigation)
Chloride	meq/L	5	Potential leaf damage
Boron	mg/L	0.5	Based on potential toxicity to lemon trees
SAR		12	Prevention of soil permeability physical soil property changes; based on the salinity limit of 2.5 dS/m

Table ES- 4. Estimated Water Quality of Blended Alamo River-Colorado River Irrigation Water

Parameter	Units	Limit	Volume of Alamo River Reclaimed, mafy			
			0	0.1	0.2	0.3
Salinity	dS/m	2.5	1.2	1.3	1.4	1.6
Sodium	meq/L	20 (5)	6.1	6.6	7.3	8.2
Chloride	meq/L	5	3.4	3.8	4.4	5.2
SAR		12	3.2	3.4	3.6	3.9

Table ES- 5. Summary of Collected Alamo River Sample Water Quality

Parameter	Units	Average	Minimum	Maximum
pH	pH units	8.04	7.56	8.29
Electroconductivity (EC)	dS/m	3.35	2.75	3.88
Total suspended solids (TSS)	mg/L	260	126	470
Total dissolved solids (TDS)	mg/L	2,310	1,850	2,600
Turbidity	NTU	80	55	105
Alkalinity	meq/L	4.3	3.8	5.0
Hardness	meq/L	17.3	16.0	19.4

Table ES- 6. Average Effluent Characteristics of Conventionally Treated Water[1]

Parameter	Units	Alum		Ferric Chloride	
		CFSE	DMFE	CFSE	DMFE
pH	pH units	7.7	7.9	7.7	7.8
Electroconductivity (EC)	dS/m	3.4	3.4	3.5	3.5
Total suspended solids (TSS)	mg/L	11	1.7	7.8	1.8
Turbidity	NTU	3.1	0.46	2.3	0.47
Silt density index (SDI)		>5	3.4	>5	3.1

[1]CFSE = coagulation/flocculation/sedimentation effluent, DMFE = dual media filter effluent

Table ES- 7. Average Effluent Characteristics of Selective Calcium Softening Treated Water[1]

Parameter	Units	CFSE	DMFE
pH	pH units	9.9	7.7
Electroconductivity (EC)	dS/m	3.2	3.3
Total suspended solids (TSS)	mg/L	8.6	1.2
Turbidity	NTU	2.8	0.31
Silt density index (SDI)		>5	3.3

[1]CFSE = coagulation/flocculation/sedimentation effluent, DMFE = dual media filter effluent

Table ES- 8. Average Influent and Effluent Water Quality for Conventional Treatment - Dual Media Filtration (DMF) and Microfiltration (CFMF) Experiments[1]

Parameter	Unit	Alamo River water	Settled Alamo River water	DMFE	CFMF, PM0.1F[2]	CFMF, PM500[2]
Turbidity	NTU	80	50	0.45	0.20	0.22
Total suspended solids (TSS)	mg/L	260	110	1.9	0.6	1.5
Silt density index (SDI)		N/A	N/A	3.3	3.9	1.8

[1]DMFE = dual media filter effluent (conventional treatment), CFMFE = continuous-flow membrane filter effluent

[2]PM0.1F = 0.1 µm Koch microfilter, PM500 = 500,000 MWCO Koch micro/ultrafilter

Table ES- 9. Measured Clean Water Flux and Permeate Flux ESPA and LFCI

Manufacturer	Type	Clean water flux, m^3/m^2-hr-kPa	Permeate flux, CFMF, m^3/m^2-hr-kPa	Permeate flux, DMF, m^3/m^2-hr-kPa
Hydronautics	ESPA	4.257E-5	2.062E-5	2.136E-5
Hydronautics	LFCI	1.935E-5	8.888E-6	9.497E-6

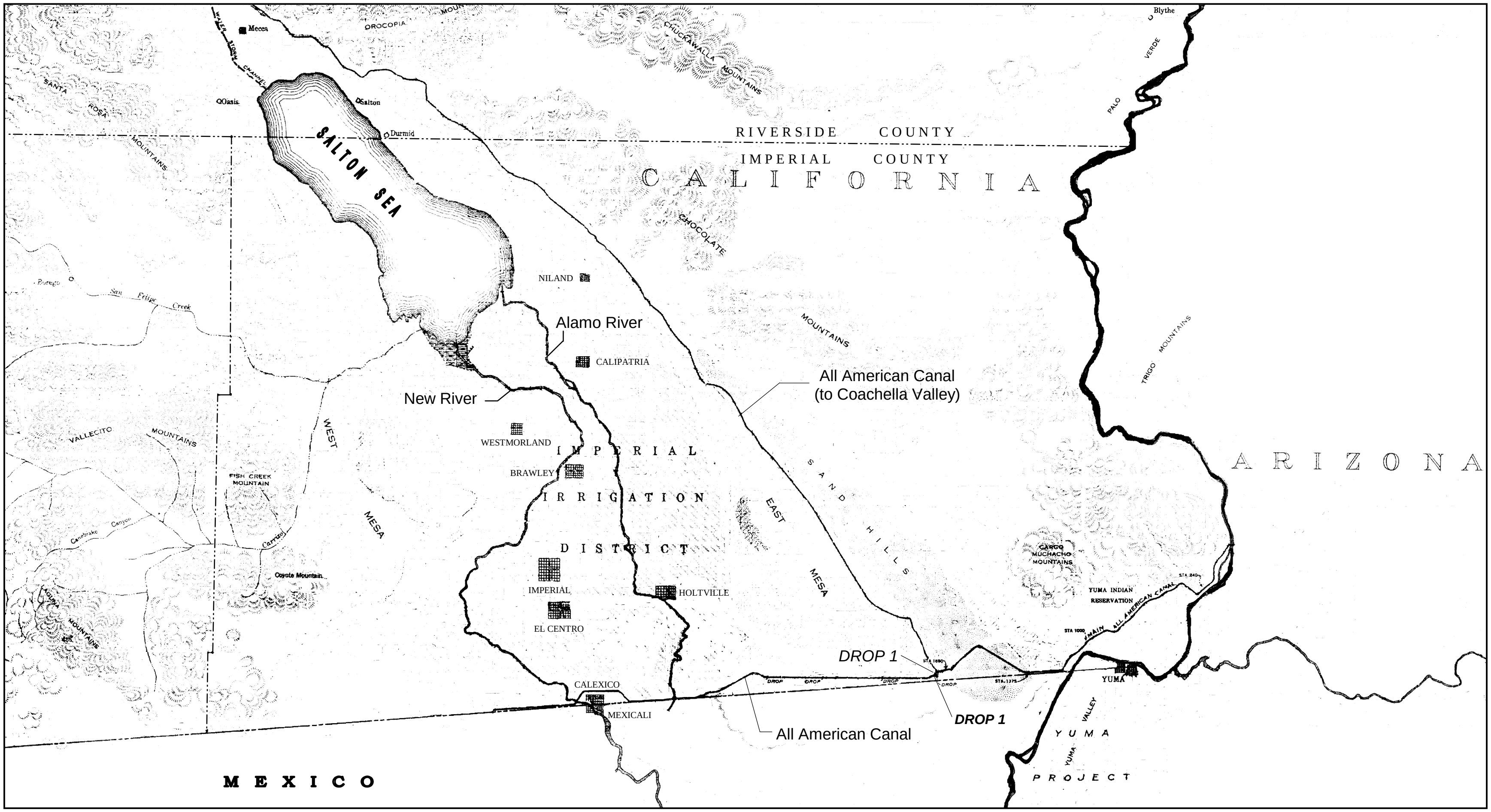

Figure ES- 1. Location of Alamo River, New River, and the Salton Sea

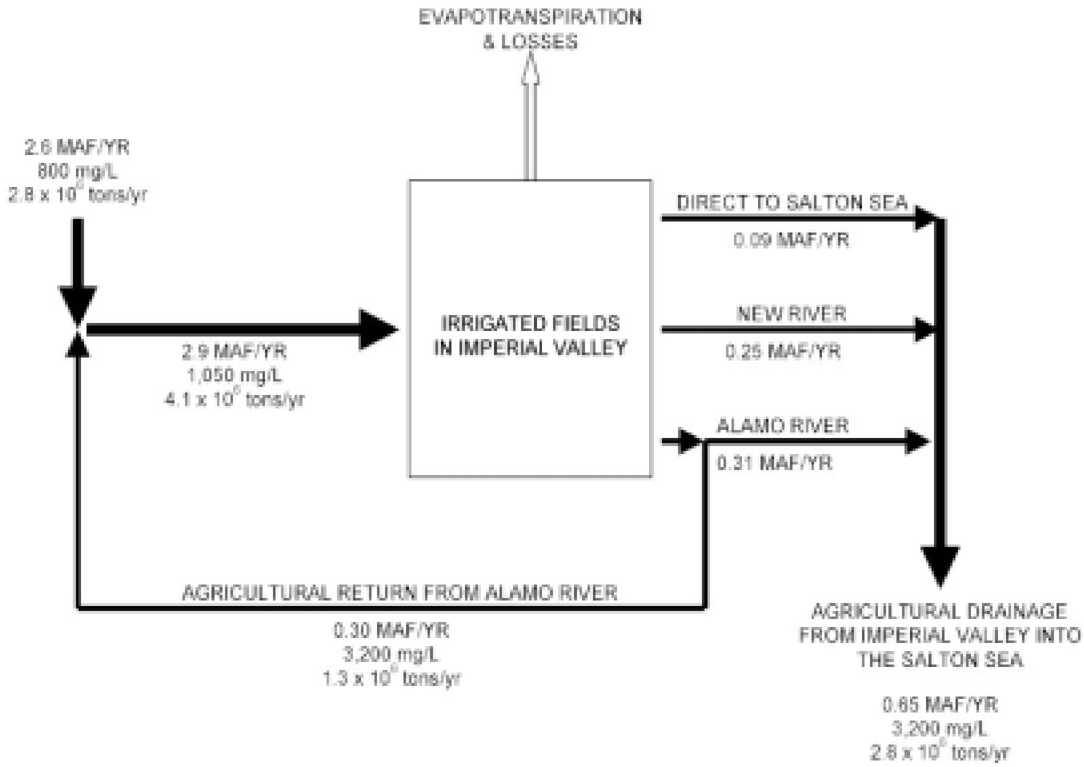

Figure ES-2. Alternative A Flow and Salt Mass Balance

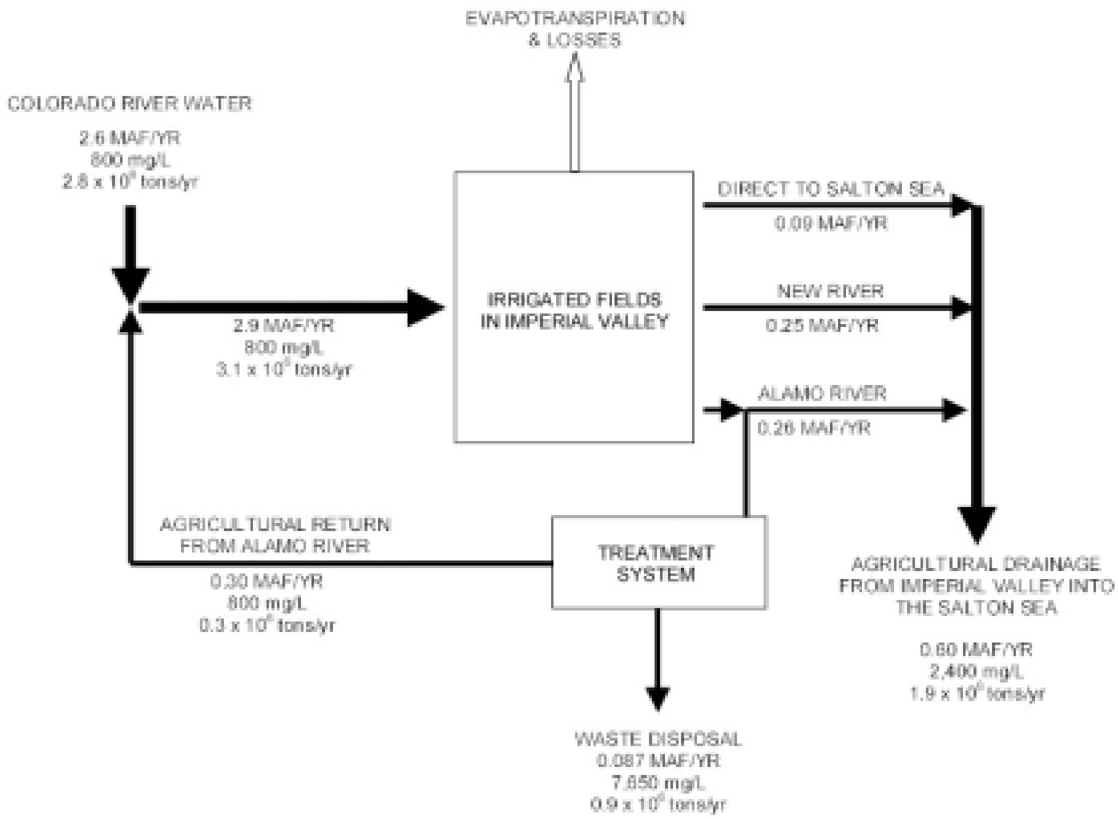

Figure ES- 3. Alternative B Flow and Salt Mass Balance

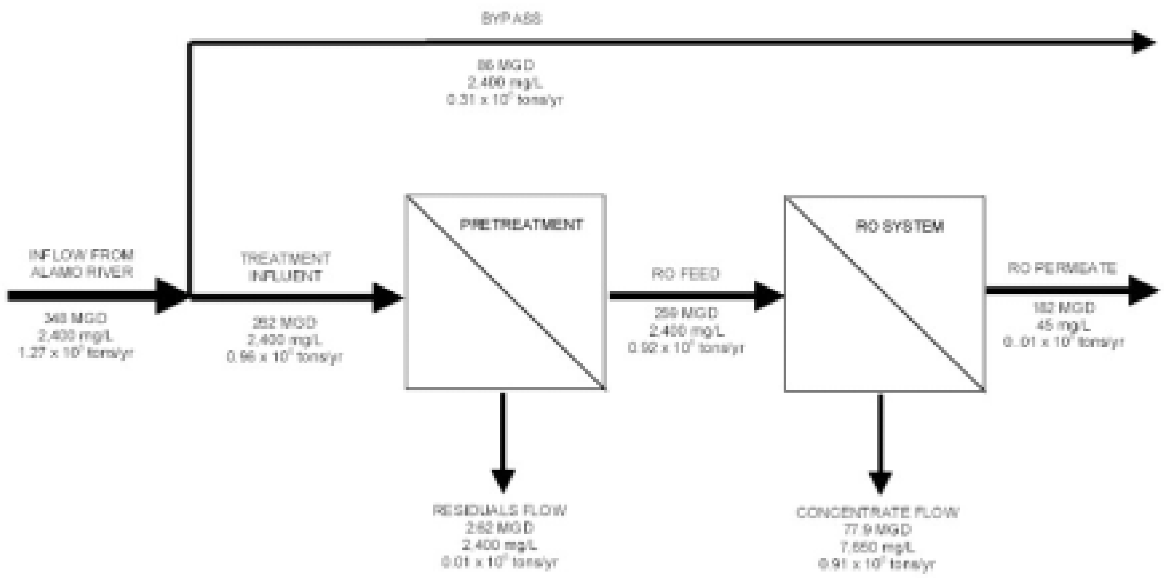

Figure ES- 4. Alternative B Treatment System and Projected Mass Balance

CHAPTER 1. INTRODUCTION

Background and Overview

Demographers predict that the population will steadily grow in Southern California over the next 50 years. As this population grows, there will be a concomitant increasing demand for water. The California Department of Water Resources (1998) estimates that by the year 2020 that there could be an annual water shortage of 1.45 million acre-feet in the South Coast and Colorado River hydrologic regions under the current water policies and resources. To ensure that current and future residents of Southern California are able to maintain the high standard of living that they enjoy, alternative attitudes and approaches concerning water supply and uses must be considered. Because increasing water demand is not limited to Southern California, it is unlikely that additional new sources of fresh water will be available. In fact, some of the existing water that Southern California presently imports may be diverted to other consumers. Therefore, at this time non-traditional sources of water, such as water reuse of municipal wastewater, agricultural drainage water, and brackish groundwater is being considered.

All of these aforementioned sources of potential reuse water require desalination to meet water quality objectives. The Desalination Research Innovation Partnership (DRIP) was established to carry out a comprehensive research program to address common issues related to the use of these non-traditional waters, such as agricultural drainage water, through desalination. As a DRIP member, the University of California, Riverside has been conducting preliminary evaluation and demonstration of agricultural drainage water reuse through this PIER I project.

With respect to reclamation of agricultural drainage waters from the Imperial Valley for municipal purposes, Black and Veatch conducted a conceptual-level study of treating and desalting agricultural drainage water, and conveying the treated product for municipal use via to the Colorado River Aqueduct (CRA) just north of the Salton Sea. They estimated that the cost for a 350,000-afy project would be $400 to $465 per acre-foot. Unit costs for a smaller 50,000-afy system would be $500 to $560 per acre-foot. Based on these estimates and other considerations, reclamation of agricultural drainage water, as an additional supply source for the CRA, was not practicable at that time.

As an alternative to this approach, it was hypothesized that if a portion of agricultural drainage waters generated in the Imperial Valley were reclaimed and reused for irrigation within the Imperial Valley, a portion of Colorado River water currently used for irrigation in the Imperial Valley, approximately 10 percent or 300,000 afy, could be exchanged for municipal purposes. Some potential advantages of this approach versus treating and desalting agricultural drainage water, and conveying the treated product to the CRA were shorter conveyance requirements; lower pumping costs; and lower treatment requirements. The work presented in this report presents a preliminary evaluation of the efficacy of reclaiming agricultural drainage water generated in the Imperial Valley for irrigation reuse.

Project Objectives

The purpose of this study was to examine the technical feasibility of reclaiming agricultural drainage water for irrigation reuse in the Imperial Valley. This objective was based on the supposition that a major source of municipal water supply could be developed if a small portion of the raw water supply currently used for agricultural irrigation be redirected for municipal purposes. However, this strategy could be implemented only if reclaiming agricultural drainage water for irrigation reuse is feasible. Suitable water must be available to replace any water diverted from agriculture.

Principal considerations in this evaluation were: (1) volume of agricultural drainage water generated in the Imperial Valley; (2) water quality characteristics of agricultural drainage water generated in the Imperial Valley; (3) irrigation water quality criteria and reuse treatment objectives for a variety of common crops; (4) strategies and treatment processes to meet required irrigation water quality criteria; and (5) experimental testing of treatment processes to confirm technical feasibility of agricultural drainage water reclamation, and to obtain preliminary system and process design and operating parameters as a prelude to a subsequent economic evaluation.

Specific objectives of this study conducted at UC Riverside were as follows:

Task 1. Characterization of Agricultural Drainage Water: Flow and Quality

Task 2. Water Quality Objectives for Agricultural Drainage Water Reuse

Task 3. Identification of Agricultural Reuse Alternatives in the Imperial Valley

Task 4. Pretreatment Process Assessment

Task 5. Salinity Removal by Reverse Osmosis

Task 6. Preliminary Evaluation of Reclaiming Agricultural Drainage Waters for Reuse

The scope of this study is limited to the agricultural drainage water generated in the Imperial Valley. Water from the Alamo River is used to be representative of agricultural drainage waters in the Imperial Valley. Nearly all of the 600,000-afy flow in the Alamo River is generated as the result of agricultural field drainage.

Report Organization

The organization of the main body of this report and the contents of each chapter are as follows:

Chapter 2. Project Approach. The approach (methods and materials) used for each of the project tasks are described in this section. Each task description begins with a summary of the approach for each task, followed by more detailed narratives.

Chapter 3. Project Outcomes. The results derived from each of the project tasks are described in this section. Each task description begins with a summary of the outcomes for each task, followed by more detailed narratives.

Chapter 4. Conclusions and Recommendations. Conclusions and recommendations based on the collective results from the project tasks are summarized.

Supplemental support materials at the end of the report include references, glossary, list of figures, list of tables, and appendixes.

CHAPTER 2. PROJECT APPROACH

The methods and materials used for each of the specific tasks for this study are summarized in this chapter. Each project task is presented under its own heading. Each task description begins with a summary of the approach for each task, followed by more detailed narratives. Because a number of tasks required fabrication of bench-scale and pilot-scale apparatuses used for testing and evaluating different water treatment schemes, the details of dimensions, operating procedures, etc. have been included in the appendixes.

Task 1. Characterization of Agricultural Drainage Water: Flow and Quality

Two important issues surrounding the feasibility of reclaiming agricultural drainage water generated in the Imperial Valley for irrigation reuse purposes are: (1) agricultural drainage water flow volume and (2) water quality. For this task a summary of agricultural drainage water quality and flows in the Alamo River in the Imperial Valley was prepared. Sources of information for this task were:

- Historical agricultural drainage water flows of the Alamo River in the Imperial Valley from the U.S. Geological Survey (1997, 2001).
- Historical agricultural drainage water quality of the Alamo River in the Imperial Valley from the U.S. Geological Survey (1997)
- During the bench-scale experimental work conducted as part of Tasks 4 and 5, agricultural drainage water collected from Alamo River was analyzed for quality.

The U.S. Geological Survey (USGS) has a flow monitoring station on the Alamo River at Drop 3 near Calipatria, California, near its mouth at the Salton Sea, Station Number 10254670. Historical water quality data from this station was obtained from its web site at http://water.usgs.gov/pubs/dds/wqn96/ and summarized for average water quality. Summarized parameters included pH, alkalinity, electroconductivity, total dissolved solids, total suspended solids, turbidity, chloride, nitrate, phosphate, sulfate, calcium, magnesium, potassium, sodium, boron, silica, and selenium. Historical flow data were also available from the USGS web site at http://s601dcascr.wr.usgs.gov/Sites/h1810.html.

During the course of the bench-scale testing as part of Tasks 4 and 5, samples from the Alamo River were collected and analyzed for quality. Sample water was collected from the U.S. Geological Survey Gaging Station, Number 10254670, on the Alamo River at Drop 3 near Calipatria, California. Water quality analyses were selected based on 1) water quality criteria for irrigation of crops grown in Imperial Valley and 2) parameters that were used to assess performance of the treatment processes to be tested. At the time of collection onsite, air and water temperature readings were recorded. Electroconductivity (EC) and pH measurements were also made with field test equipment. Grab raw water samples were collected for total suspended solids (TSS), particle size distribution, total dissolved solids (TDS), electroconductivity (EC), pH, turbidity, alkalinity, and hardness. In addition, cationic metal species were determined via inductively coupled plasma (ICP) spectroscopy. Analyses were conducted in accordance with widely accepted analytical methods for water and wastewater analysis (Standard Methods, 1989).

Task 2. Water Quality Objectives for Agricultural Drainage Water Reuse

The purpose of this task was to identify acceptable water quality criteria for crops grown in the Imperial Valley. The steps used for completing this task were as follows.

- Water quality criteria for irrigation water used in the Imperial Valley were defined based on the available agricultural irrigation research studies and on the available soil and crop data for the Imperial Valley. Based on these water quality criteria, water quality objectives and treatment needs for agricultural drainage water reuse were formulated.

- Alternative water quality treatment objectives for reclaimed agricultural drainage water were developed on the basis of the quality of the Colorado River Water currently used for irrigation within the Imperial Valley.

Irrigation water quality criteria were developed specific to agricultural practice in the Imperial Valley. These water quality criteria were based on agricultural water quality guidelines established by the University of California Division of Agricultural and Natural Resources (DANR) (Hanson et al., 1993). These guidelines vary with crops and climate. As such, information regarding the acreage of crops grown in the Imperial Valley was collected and the crop data correlated with the water quality guidelines to establish the irrigation water reuse criteria. Minimum reuse criteria for agricultural drainage water reuse were established based on the premise that the reuse strategy must not affect crop yields significantly in the Imperial Valley, and thereby decrease the crop value per acre as the result of reuse of agricultural drainage water. Imperial Valley crop data were obtained from the U.S. Bureau of Reclamation (Jensen and Walter, 1997).

Since the development of Imperial Dam and the All-American Canal during the 1910s and 1920s, water used for irrigation in the Imperial Valley has come exclusively from the Colorado River. Thus, there is likely to be strong reluctance by the farmers to accept lower quality water caused by agricultural drainage water reuse, even though crop yields and values may be unaffected. In anticipation of this reluctance, alternative treatment objectives for agricultural drainage water were developed on the basis of the historical Colorado River water distributed by the Imperial Irrigation District from the Imperial Dam reservoir. Historical Colorado River water quality data were obtained from the USGS via its web site at http://water.usgs.gov/pubs/dds/wqn96/.

Task 3. Identification of Agricultural Reuse Alternatives in the Imperial Valley

On the basis of minimum reuse criteria developed in Task 2 for agricultural drainage water reuse that will not affect crop yields significantly or decrease crop value per acre, an agricultural drainage water reuse alternative that will provide reclaimed water from the

Alamo River for irrigation was formulated. This alternative, designated Alternative A, was developed on the basis of the Alamo River water quality and the treatment requirements to meet the minimum reuse criteria.

A second reuse alternative was developed on the premise that may be strong reluctance by the farmers to accept lower quality water caused by agricultural drainage water reuse, even though crop yields and values may be unaffected. A second agricultural drainage water reuse alternative, designated Alternative B, was forwarded on the basis of the Alamo River water quality and the treatment requirements needed to ensure that the delivered reclaimed irrigation water was similar in quality to that of the Colorado River.

A target flow reuse volume of 300,000 acre-feet per year was selected for both alternatives. This volume is approximately 10 percent of the total Colorado River water apportionment to the Imperial Irrigation District (IID).

Task 4. Pretreatment Process Assessment

Pretreatment of the feed is necessary in reverse osmosis (RO) desalination treatment to minimize membrane fouling. While all RO membranes experience flux decline with operation time, fouling and scaling increases the rate of flux decline, increasing the frequency of membrane cleaning and replacement. Common RO fouling mechanisms include scaling, principally calcium carbonate ($CaCO_3$) or calcium sulfate ($CaSO_4$); colloidal plugging; and biological slime formation. For RO systems to operate cost effectively and efficiently, pretreatment systems must remove turbidity and suspended solids, reduce the tendency of the water to form scale, and prevent biological slime growth. Suggested pretreated water quality requirements for RO membranes to minimize non-biological fouling are turbidity less than 1.0 NTU and a silt density index (SDI) <5 (Osmonics, 2000). In addition, the expected concentrations of calcium, carbonate, and sulfate in the concentrate stream should not be over saturated with respect to calcium carbonate and calcium sulfate scale formation.

For Task 4, three different schemes for agricultural drainage water reuse as pretreatment for salinity removal by RO treatment were evaluated. The pretreatment strategies evaluated are listed below. Evaluation of these three pretreatment strategies was conducted using bench-scale experimental testing.

- Conventional Treatment. This strategy consisted of sequential coagulation, flocculation, sedimentation, and granular-medium filtration.

- Selective Calcium Softening. This strategy consisted of sequential lime-soda ash softening, sedimentation, and granular-medium filtration.

- Membrane Filtration. This strategy consisted of either microfiltration (MF) and ultrafiltration (UF) treatment.

In Task 3, it was determined that Alternative A required that treatment was not required if up to 300,000 aft of water from the Alamo River could be reblended with fresh Colorado River irrigation water at the initial IID distribution in the All-American Canal system. The resultant blended water, although lower in quality, should result in minimal adverse impact on crop yield and value. Thus, bench-scale treatment process evaluation conducted in Task 4 and Task 5 are only applicable to Alternative B (see Task 3 above).

Source Water

The source water for the experiments in Task 4 and Task 5 was the Alamo River. Sample water was collected from the U.S. Geological Survey Gaging Station, Number 10254670, on the Alamo River at Drop 3 near Calipatria, California. The general procedure for each source water collection episode was to pump Alamo River water from the pool behind the gaging station weir into 55-gallon drums for transport to the UCR Environmental Engineering Laboratory (300-mile round trip). The number of drums collected varied from six to twelve depending on need and load capacity of the available truck.

At the time of collection onsite, air and water temperature readings were recorded. EC and pH measurements were also made with field test equipment. Grab raw water samples were collected for TSS, TDS, EC, pH, and turbidity, alkalinity, and hardness analyses. In addition, cationic metal species were determined via inductively coupled plasma (ICP) spectroscopy. Analyses were conducted in accordance with widely accepted analytical methods for water and wastewater analysis (Standard Methods, 1989). Particle size distributions were determined using a Coulter Counter (Multizizer II) using procedures provided by the manufacturer.

Also, at the time of sample collection, settleable solids' testing was conducted using standard one-liter Imhoff cones. One-liter aliquots of Alamo River sample were allowed to settle one hour in the Imhoff cones and supernatant were collected for later TSS, particle size distribution, and turbidity measurements. In addition, sample aliquots of Alamo River water that were allowed to settle overnight were analyzed for TSS and turbidity. These tests were conducted to provide a semi-quantitative assessment of the settleability of Alamo River suspended solids without coagulant addition (plain sedimentation).

Jar Testing

The bench-scale evaluations of the pretreatment strategies were preceded by extensive jar testing to narrow the number of possible combinations of operating parameters evaluated using the bench-scale water treatment system.

Jar tests simulate chemical coagulant addition, rapid mix, and flocculation water treatment units. The basic jar test consists of chemical coagulant addition, followed by a short rapid mix cycle, a longer flocculation cycle, and finally a sedimentation period. For this study, jar testing was conducted using a Phipps & Bird Six-Paddle Stirrer apparatus and included a rapid mix and three slow-mix or flocculation steps. For each jar test set, two-liter samples were placed into each of six jar-test reactors. Coagulant and/or softening agents at varying doses were added to five of the six reactors. One reactor without coagulant added was used as a control.

The mixing power input and time duration of the cycle characterize both the rapid mix and flocculation steps. The measure of mixing input is specified by the G value, which is the mean velocity gradient, given by the equation $G = [P/V\mu]^{1/2}$ where P is the power input per unit volume, μ is the dynamic viscosity of water, and V is the flocculator volume. Typical average G values used in rapid mixers range from 500 to 1000 s^{-1}. For flocculators, typical G values used in water treatment range from 10 to 80 s^{-1}. Detention times in rapid mixers vary from 30 seconds to 2 minutes. Detention times in flocculators range from 15 to 60 minutes (Reynolds and Richards, 1995).

During jar testing, mixing/flocculation paddles were immersed into the samples immediately after chemical coagulant was added to the jars. The stirrer was initiated at 300 rpm (G = 600 s^{-1}) for one minute to simulate the rapid mix cycle. At the end of the rapid mix cycle, three successive slow-mix steps were used to simulate tapered flocculation, which is typically employed in water treatment plants. Tapered flocculation optimizes the development of floc particles by promoting a high rate of particle collisions in the first stage of flocculation and promoting floc size growth in the subsequent stages. Particle collision rate and floc growth is controlled by the mixing power input to each flocculation stage. The G value is highest in the first stage and lowest in the third stage. The overall flocculation process is described by the average G value of the three stages.

For these experiments average G values of 60, 40, and 20 s^{-1} were used. Experimentally, adjusting the stirrer speed modified the G value for each flocculation step. The highest stirrer speed was maintained for 10 minutes and then reduced to the second rpm setting for another 10 minutes. Following this second 10-minute period, the stirrer speed was reduced to the third and final rpm setting. Summarized G values for each of the three flocculation stages for each average G value are given in Table 1.

After the third 10-minute flocculation period, the stirrer was stopped and the contents of the reactors were allowed to settle for 60 minutes. Following this settling period, supernatant was collected from each reactor for turbidity analysis. Detailed jar test procedures are included in Appendix A.

Historical records indicate that the temperature of the Alamo River varies from about 12^{o}C in the winter to about 30^{o}C in the summer. The effect of temperature on the coagulation-flocculation-sedimentation process was studied by placing sub-samples of a common Alamo River water sample into warm and cold temperature incubators, set at 32^{o}C and 10^{o}C, respectively. After allowing these sub-samples to equilibrate overnight, jar tests were performed on the temperature modified water samples. These jar tests were performed at room temperature using an average G value of 40 s^{-1}. Therefore, temperature change occurred during the tests. The final measured temperatures of the jar contents were 31^{o}C and 12^{o}C after the sedimentation period.

Alum (aluminum sulfate) and ferric chloride are common coagulants used in water treatment practice. The effectiveness of these two coagulants for Alamo River water was evaluated using jar tests. In addition, lime-soda ash softening was evaluated using jar tests. Three sets of jar tests were performed for ferric chloride and alum coagulants, as well as softening. The first set of jar tests was performed to estimate optimum coagulant dose and G value. The effect of temperature was studied in the second sets of jar tests. The third set of jar tests was conducted in conjunction with the bench-scale continuous-flow conventional treatment to determine optimum coagulant dose for the particular Alamo River sample being tested (see later section). The overall test matrix for the jar tests is presented in Table 2.

Conventional Treatment Bench-Scale Testing

Evaluation of both conventional treatment and selective calcium softening were conducted using a common bench-scale testing system that consisted of two primary components - an integrated coagulation, flocculation, and sedimentation system; and a set of three dual-media filters. The bench-scale coagulation, flocculation, and sedimentation (CFS) unit and the dual-media filters (DMF) used in this study were designed and constructed specifically for this project. The purpose of these units was to provide reasonable simulation of full-scale systems with good experimental control, yet sufficiently small that a discharge permit would not be required. Its intent was also to provide a tool for future deployment at a field location for a later study.

The CFS system was an integrated chemical mixing chamber, three-stage flocculator, and inclined-plate sedimentation tank apparatus. The design flow for the CFS system was 2 L/min, (0.5 gal/min). For a typical 300-gallon Alamo River sample, the system could be operated for about 10 hours. Specifications for the bench-scale CFS system are summarized in Table 3.

Three parallel DMF units were constructed to test different filtration rates in parallel. The collective design flow for the three DMF units was 1 L/min. The DMF units were made of acrylic plastic and were 2-in (5 cm) in diameter, and 10 ft tall (3 m). The media consisted of 24 inches of anthracite (effective size = 1.5 mm) and 8 inches of sand (effective size = 0.7 mm). These filters were operated in a constant inflow mode with a gravel underdrain. Filtration runs for this study were limited to 12 hours.

For the conventional treatment bench-scale testing experiments, the CFS system was first initiated by starting the influent flow of Alamo River water through the system, starting the chemical feed pumps, and initializing the rapid mix and flocculation mixers. Once initiated, the pumps and mixing/flocculation speeds were calibrated for the test run. Effluent from the CFS was disposed for the first three hours of operation to allow the system to reach quasi-steady state. The CFS system had an overall detention time of about one hour. Thus, three hours represents three hours detention time. After the third hour of operation, CFS effluent was collected into an intermediate transfer tank to feed the DMF units. Also, beginning at t = 3 hours, grab samples from the CFS taken every two hours for water quality analyses. Detailed CFS procedures are included in Appendix B.

As noted above, feed water for the DMF units was CFS-treated Alamo River water. Water from the intermediate tank was pumped into the three parallel DMF units, which were operated at 2, 4, and 6 gal/ft^2-min (5, 10, and 15 m^3/m^2-hr). Beginning at t = 1 hours, grab samples from each DMF unit was taken for water quality analyses. To obtain sufficient sample volume for the SDI test, effluent from the three DMF units were combined to form a composite sample that was used for particle size analysis and silt density index (SDI) analysis. Also, during the DMF filter runs the applied head, measured as water level above the media, was monitored with time. Detailed DMF procedures are included in Appendix B.

Effectiveness of the overall conventional treatment system, CFS plus DMF, for RO pretreatment was based on effluent turbidity, TSS, SDI, and particle size analysis. Turbidity and TSS analyses were performed in accordance with Standard Methods (1989). Particle size distributions were determined using a Coulter Counter (Multisizer II) using procedures provided by the manufacturer. SDI measurements were conducted according to procedures outlined by Schippers and Verdouw (1980).

Selective Calcium Softening Treatment

Bench-scale testing of selective calcium softening treatment was conducted using the same CFS and DMF units used to evaluate conventional treatment. The major difference in operation from when alum and ferric chloride coagulation was tested was that lime slurry and soda ash solution was also added to the rapid mix chamber at a dosage rate of 175 mg/L and 240 mg/L, respectively. These dosages are the theoretical amount of lime and soda ash to precipitate out the calcium hardness in the Alamo River Water. In addition, to prevent cementation of the DMF units, the pH of the CFS effluent was adjusted to between 7 and 8 by the addition of technical grade concentrated sulfuric acid.

Effectiveness of the overall selective calcium treatment system for RO pretreatment was based on effluent turbidity, TSS, SDI, and particle size analysis. Calcium reduction was also measured. Turbidity, calcium, and TSS analyses were performed in accordance with Standard Methods (1989). Particle size distributions were determined using a Coulter Counter (Multisizer II) using procedures provided by the manufacturer. SDI measurements were conducted according to procedures outlined by Schippers and Verdouw (1980).

Membrane Filtration - Microfiltration (MF) and Ultrafiltration (UF)

Size exclusion membrane filtration is a solids/liquid separation process designed to produce water essentially devoid of suspended solids and turbidity. In size exclusion membrane filtration, differentiation is often made between MF and UF. Both membrane processes are characterized by particle removal by screening using a medium having a pore size in the range from approximately 0.001 μm to 1 μm. A complicating factor is that pore size ratings for MF membranes are given in actual pore sizes while a UF membrane is described chiefly by its molecular mass cutoff (MMCO) or molecular weight cutoff (MWCO). In either case, the hydraulic performance of the membrane can be determined by conducting pure water flux experiments. The designated size range of the UF/MF membrane refers to the pore size itself and/or the retention rate for selected substances of known molecular weight.

Improved methods for minimizing fouling and clogging of the MF/UF membranes have led to its consideration as economically favorable alternative to conventional water treatment (coagulation, flocculation, sedimentation, media filtration) for certain kinds of feed waters. Hence MF and UF were consideration as a pretreatment strategy for RO desalination in this study.

Bench-scale testing was carried out using 1) a stirred-cell-apparatus and 2) continuous flow test units using agricultural drainage water from Alamo River as feed.

Stirred-Cell Apparatus (Dead End UF)

Permeate flux experiments using UF membranes were carried out using a stirred-cell-apparatus (Amicon, Model 8200, Beverly, MA) to determine the flux behavior at increasing influent concentrations and transmembrane pressures (TMPs). Feed water was delivered to the stirred-cell via a pressurized feed tank held at constant pressure using compressed nitrogen gas. A schematic of the stirred-cell-apparatus is shown in Figure 1. The contents of both the feed tank and the stirred cell were continuously mixed using a magnetic bar and stirrer. The magnetic stirrer was calibrated to predict and control the shear rate, G, within the stirred cell. The mass of filter permeate was measured continuously using an electronic balance (Denver Instrument, Model 2102, Arvada, Colorado). A PC that interfaced with the balance through an RS-232 serial port connection and a data acquisition software program recorded total mass as a function of time, and then converted to flux. Flat-sheet UF (Amicon Brand, Millipore Corp., Bedford, Massachusetts) membranes were procured of two types, ZM500 and YM 10, which designates the molecular weight cutoff (MWCO) of 500,000 and 10,000 Dalton, respectively.

Individual experiments were conducted at constant temperature, e.g. ambient laboratory temperature 21-23 °C, and constant cross-flow velocity (stirring rate). Flux readings were obtained at TMPs of 10, 20, 30, 40, and 50 psi. TMP was increased from lowest to highest value in a stepwise fashion to avoid biasing the limiting flux determination caused by solids accumulation at the membrane surface. The membrane filter was discarded upon completion of each experiment.

Continuous-Flow Re-Circulating MF/UF System (CFMF)

The laboratory-scale CFMF system used in this study was designed and constructed specifically for this project, and similar to the bench-scale CFS and DMF units, it can also be deployed to a field location for a later study. A schematic of the laboratory-scale CFMF system is provided in Figure 2.

Feed solutions, raw or settled raw Alamo River water, were pumped (Grundfos, Model CR-4, Fresno, California) from a 55-gallon feed tank (Nalgene, Nalge Nunc International, Naperville, Illinois). Concentrate return flow rate, or cross-flow rate, was measured with a flow meter (Bürkert, Model 8035 Flow Meter, Ingelfingen, Germany). Average TMP was calculated as the average of the measured inlet and outlet pressures. Pressure was controlled by adjusting the pump bypass valve and the concentrate return flow valve (see Figure 2). Feed temperature was controlled using a copper tube heat exchanger placed in the feed tank. The rapid circulation of feed through the bypass pipe maintained feed homogeneity and temperature, rendering additional mechanical mixing unnecessary.

Two continuous-flow MF/UF membrane modules (Koch Membrane Systems, Inc., Wilmington, Massachusetts), PM500 and PMF0.1, were investigated in this study. The membranes were of the hollow fiber configuration, where the membrane is in the form of hollow fibers that are bundled together and placed in a cylindrical cartridge. Each end of the bundle is potted in epoxy and trimmed allowing the feed water to be pumped through the inside of each fiber and the permeate to exit from the fiber wall while the retentate is recirculated back into the feed tank. This configuration also allows for periodic backflushing, maximizing yield and filter longevity. Specifications for the PM500 and PMF0.1 MF membranes are summarized in Table 4.

The process parameters evaluated as a part of these membrane filter experiments were influent solids concentration in the Alamo River water and TMP. The average TMP was calculated as the difference between the average of the inlet and outlet pressures and the pressure in the permeate line.

The membrane filtration system was operated in the recycle mode at pre-selected TMP values and a uniform cross-flow velocity until steady state permeate flux was reached. The pre-selected TMP pressures were 7.5, 17.5, and 27.5 psi (50, 120, and 190 kPa) for the PM500 membrane and 7.5, 12,5, 17.5, and 22.5 psi (50, 85, 120, and 150 kPa) for the PMF0.1 membrane. When the permeate flow reached a steady value (between 0.5 and 1.5 hours), the TMP was increased and the experiment repeated. A constant cross-flow rate of 0.12 L/s was maintained by keeping the pressure differential along the cartridge membrane, P_{inlet} - P_{outlet}, constant at 5 psi. for all TMP excursions. Upon completing each experiment, the system was flushed and back-flushed according to the manufacturer's specification to remove feed water residuals remaining in the membrane housing, pump, and piping, and the clean water flux was measured. Permeate water quality was determined at the highest TMP by measuring the permeate turbidity, TSS, SDI, and particle size distribution.

Task 5. Salinity Removal by Reverse Osmosis

As a semi-quantitative evaluation of RO feasibility, a conceptual design for the RO system was developed using a membrane system software design package (*Winflows*, Version 1.2, developed by Osmonics 1999). This software package can be used to select suitable RO elements, develop a RO treatment array, estimate maximum recoveries, and identify potential scale fouling conditions and suggest possible remedies.

Bench-scale continuous flow test-cells for flat-sheet membranes (1.25" × 3.25") were used to determine the flux behavior of selected RO membranes and to generate water for assessing membrane desalination efficiency. The RO sheet test-cell apparatus is shown in Figure 3.

Feed solutions, obtained following conventional treatment, selective calcium treatment, or membrane filtration treatment, were pumped from a 5-gallon feed tank (Nalgene, Nalge Nunc International, Naperville, Illinois) using a turbine pump (Procon, Model 0400, Murfreesboro, TN) with an electric pump motor (Dayton, Model 2R958, Niles, IL). The TMP was regulated by needle valves on the feed inlet and return lines, and was set on the basis of pre-selected pressures that were monitored via pressure gauges at both inlet and outlet sides. Rapid feed circulation precluded the need for mechanical mixing. Temperature of the feed was controlled using a copper tube heat exchanger placed in the feed tank.

Similar to the stirred-cell UF apparatus, permeate mass was measured continuously using an electronic balance (Denver Instrument, Model 2102, Arvada, Colorado) interfaced with a PC and a data acquisition program. Two types of flat-sheet RO membranes (Hydranautics, Oceanside, California) designated ESPA and LFCI were used in this study. Individual experiments were conducted at ambient laboratory temperature 21-23°C, and constant cross-flow velocity. Flux readings were obtained at TMPs of 50, 75, 100, and 125 psi. The recirculation rate was 0.16 gal/min (0.606 L/min). Selected membrane filters were kept upon completion of selected experiment for subsequent scanning electron microscopy (SEM) analysis of the membrane surfaces for signs of chemical deposition and fouling. Permeate samples were analyzed for TDS, alkalinity, pH, and cation metal concentrations.

Task 6. Preliminary Technical Feasibility Evaluation of Reclaiming Agricultural Drainage Waters for Reuse

The purpose of this task was to evaluate the technical feasibility of reclaiming agricultural drainage water for irrigation reuse, and thereby create opportunities for increasing water availability for municipal use in Southern California.

In evaluating the technical feasibility several factors were considered including:

- Water volume: Is there a sizeable volume of water from a readily available source that can be treated to provide a meaningful supply of water for municipal use?

- Crop water use: Can agricultural drainage water be reused directly without adversely affecting crop yields?

- Treatability: Can the agricultural drainage water be treated using standard, commercially available treatment technologies to achieve the desirable treatment goals?

The technical evaluation with regard to available water volume and flow is based on the Colorado River Seven Party Agreement whereby the Imperial Irrigation District (IID) is entitled to 2.9 of the 4.4 million acre-feet per year entitlement to California. It is further assumed that agricultural practices will not change appreciably in the future and that agricultural drainage volumes will remain approximately one third of the irrigation water volume.

Similarly, the technical feasibility for reusing agricultural drainage water has been assessed by examining the water quality parameters that affect crop yields. Water quality parameters include pH, alkalinity, electroconductivity, total dissolved solids, total suspended solids, turbidity, chloride, nitrate, phosphate, sulfate, calcium, magnesium, potassium, sodium, boron, silica, and selenium. The minimum reuse criteria for agricultural drainage water reuse will be based on the premise that the reuse strategy must not affect crop yields significantly in the Imperial Valley, and thereby decrease the crop value per acre as the result of reuse of agricultural drainage water.

The technical feasibility for treating agricultural drainage water using standard, commercially available, treatment technologies was assessed from bench-scale treatability experiments. Specifically, pretreatment should yield effluent water with turbidity less than 1 NTU and SDI <5 (Osmonics, 1999) to ensure adequate RO performance in subsequent desalination steps.

CHAPTER 3. PROJECT OUTCOMES

The results and outcomes from each of the specific tasks conducted for this study are summarized in this chapter. Each project task is presented under its own heading. Each section begins with a summary of the results for each task, followed by more detailed narratives.

Task 1. Characterization of Agricultural Drainage Water: Flow and Quality

Summary of Task 1 Outcomes

- Nearly all of the flow in the Alamo River is due to agricultural drainage water. The historical annual flow rate of the Alamo River, which empties into the Salton Sea is 600,000 afy (830 ft^3/s).

- The average historical total dissolved solids concentration of the Alamo River is about 2,400 mg/L, or about three times the TDS concentration of the Colorado River. The Alamo River also has a high sediment concentration. The average historical TSS concentration and turbidity values are 540 mg/L and 127 NTU, respectively.

- During this study, the average measured TDS of the sampled Alamo River water was found to be 2,300 mg/L, or less than 5 percent difference from the historical average. However, the average measured TSS concentration and turbidity value were found to be 260 mg/L and 80 NTU, respectively. These values are substantially lower than the historical averages.

Agricultural Drainage Flow

Agriculture in the Imperial Valley relies on irrigation water from the Colorado River via the All American Canal. Based on the Colorado River Seven Party Agreement, the Imperial Irrigation District (IID) is entitled to 2.9 of the 4.4 million acre-feet per year entitlement to California. Of the 2.9 million acre-feet per year IID entitlement, about 2.6 million acre-feet per year are delivered to users. Seepage losses, evaporation and water used for hydraulic control accounts for the remaining 0.3 million acre-feet per year.

To prevent salinity buildup in the soil, irrigation water in excess of the consumption use demand of the crops (due to evapotranspiration) must be applied to the fields. Excess water, which percolates through the soil column, is referred to as the leaching fraction. The leaching fraction carries away salts from the root zone and is collected by a system of drain tiles that are typically located six feet below the soil surface.

In addition to the leach fraction there are additional water flows that drain from an agricultural field: tailwater, operational diversion, and seepage. Tailwater is excess irrigation water that runs off the surface of the fields. Operational diversion is water that is not applied directly to the fields, but is used for gravity flow control. Seepage is water from the irrigation canals. These drainage waters are collectively referred to as agricultural drainage water.

Agricultural drainage waters from the various fields are collected in a series of unlined drainage canals and drainage laterals that are analogous to a municipal storm or sanitary sewer system. These canals and laterals ultimately discharge into the Alamo River, the New River, or directly into the Salton Sea. Locations of the Alamo River and the New River in relation to the Salton Sea are shown in Figure 4. Agricultural drainage water from the Imperial Valley into the Alamo River and New River accounts for about 80 percent of the total flow into the Salton Sea.

Approximately 850,000 acre-feet of agricultural drainage flow into these two rivers. Nearly 100 percent of the Alamo River's average annual flow of 600,000 acre-feet is agricultural drainage. However, only 57 percent of the New River's average annual flow of 450,000 acre-feet is comprised of agricultural flow. The remaining 43 percent of New River flow comes from Mexico, which is comprised of both agricultural drainage and minimally treated municipal wastewater. A summary of inflows based on recent U.S. Geological Survey data is presented in Table 5.

From the perspective of a water reclamation project in the Imperial Valley, the Alamo River offers the best opportunity to obtain a large volume of water that can be generated for reuse. Unlike the New River, which receives nominally treated municipal wastewater from Mexico, the Alamo River is composed almost exclusively of agricultural drainage water. Thus, risks that may occur due to the presence of pathogenic organisms will be far less if the Alamo River is used as a reclamation water source.

Alamo River Water Quality - Historical Data

Imperial Valley agricultural drainage water is brackish. The measured average TDS of the Alamo River is around 2,400 mg/L (USGS, 1997). This value is consistent with the concentration of salinity associated with the imported irrigation water. The average TDS of Colorado River water used for irrigation is about 800 mg/L, and the agricultural drainage volume is approximately one third of the applied irrigation water. Assuming that there is no net accumulation of salt in the soil, the TDS of the resulting drainage water should be three times that of the applied water, which it is. Average water quality data for the Alamo River based on USGS measurements near Calipatria are summarized in Table 6.

Alamo River Water Quality - This Study

The source water for the bench-scale experiments, Tasks 4 and 5, was the Alamo River. Sample water was collected from the U.S. Geological Survey Gaging Station, Number 10254670, on the Alamo River at Drop 3 near Calipatria, California. Average water quality of the collected samples, as well as the measured concentration ranges, are summarized in Table 7. For many of the parameters, the measured concentrations are similar to the reported historical averages. However, the average measured TSS concentration and turbidity value were found to be 260 mg/L and 80 NTU, respectively. These values are substantially lower than the historical averages. These reductions may be due to recent efforts to control sediment runoff in the agricultural drainage water from the fields (Allred, 2001).

Task 2. Water Quality Objectives for Agricultural Drainage Water Reuse

The first step in developing an overall strategy for an agricultural drainage reclamation project for irrigation was to establish acceptable water quality criteria for the intended irrigated crops. In this section, water quality criteria for crops and soils are presented and a projection of treatment goals for agricultural drainage water from the Alamo River is made.

Summary of Task 2 Outcomes

- The principal water quality parameters of concern in regard to the reuse of Alamo River Water for irrigation in the Imperial Valley are salinity (measured as EC), sodium, chloride, boron, and sodium absorption ratio (SAR).

- Suggested guidelines for acceptable water quality are delineated below.

Parameter	Units	Limit	Reason
Salinity	dS/m	2.5	Higher salinity may result in greater than 10% reduction in relative crop yield
Sodium	meq/L	20 (5)	Sodium toxicity (Leaf damage through spray irrigation)
Chloride	meq/L	5	Potential leaf damage
Boron	mg/L	0.5	Based on potential toxicity to lemon trees
SAR		12	Prevention of soil permeability physical soil property changes; based on the salinity limit of 2.5 dS/m

Effect of Water Application Rate on Salinity

The average root zone soil salinity is a function of the irrigation water salinity and the leaching fraction. The leaching fraction (LF) is defined as the percent of applied irrigation water, minus any surface runoff, that drains below the root zone. The average root zone salinity, EC_e, can be estimated from the irrigation water salinity, EC_w, using the family of curves shown in Figure 5. A common relationship for estimating EC_w from the total dissolved solids (TDS) concentration is EC (dS/m) = TDS (mg/L)/640 (Hanson et al., 1993).

Based on a 1994 study by IID (Black and Veatch, 1997), it was estimated that about 16 percent of the applied water to fields ran off the fields as tailwater, 10 percent was lost due to operational discharges (for flow distribution control, and 17 percent was collected from subsurface infiltration. Subtracting the tailwater and operational discharges, the average leaching fraction in the Imperial Valley is approximately 23 percent (100(17)/(100-10-16)). The average TDS of Colorado River water used by IID for irrigation is about 820 mg/L, or an EC_w of 1.3 dS/m. From Figure 5, the estimated average root zone salinity is 1.9 dS/cm.

The average EC_w of Alamo River water is about 3.5 dS/m. The salinity of Alamo River is more than 2.5 times that of the Colorado River. The estimated average root zone salinity would be 5.0 dS/cm if Alamo River water were used directly for irrigation with no treatment or dilution with Colorado River water.

Effects of High Salinity on Agriculture Crops and Soils

Salinity in irrigation water can reduce crop growth and yield in two ways, by osmotic influence and specific ion toxicity. Specific ion toxicities for field and garden crops include sodium, chloride, and boron toxicities. Salinity may also affect the availability of crop water and hence have a negative effect on agricultural production due to modifications of soil structure and soil-water permeability.

Osmotic Effects

Osmotic influence is the most common adverse effect on crop growth and yield. Under normal, non-salinized conditions, the concentration of salts in plant roots are higher than that in the soil water allowing water to diffuse freely into the plant root by osmosis. As the salinity of the soil water increase, the difference in salt concentration between the root and soil water decreases, making the water less available to the plant. To compensate for the drop in water availability, the roots adjust osmotically by accumulating more salt within the plant (halophytes) or synthesizing organic acids (glycophytes) to maintain the favorable osmotic conditions to take up water. These processes use energy that would normally be used for plant growth. The end result is that the plant is smaller and has a lower crop yield. Plants differ widely, however, in their response to salinity.

Plant salt tolerance is defined as the extent to which the relative growth or crop yield is decreased when the crop is grown in a salinized environment as compared to a non-salinized environment. Most crops can tolerate soil salinity up to a given threshold. Beyond the threshold value, crop yield declines linearly with salinity. The relationship between relative yield and soil salinity is typically described as:

$$Y = 100 - B(EC_s - A)$$

where Y = relative yield (%), EC_s = average root zone soil salinity (dS/m), A = threshold EC_s value at which 100% yield occurs, and B = slope of decline line (percent yield reduction per increase in average root zone soil salinity). Values of A and B for the major crops grown in the Imperial Valley are listed in Table 8. About 80 percent of the total irrigated acreage in the Imperial Valley consists of field crops (450,000 acres); 17 percent garden crops (95,000 acres), and 3 percent permanent crops (20,500 acres). Relative yields as a function of EC_s for most of the crops listed in Table 8 are summarized in Table 9. The range of EC_s values reported in Table 9 represents Colorado River water on the low end and Alamo River water on the high end. Thus, the impact of increasing salinity on relative crop yield can be seen. Most of the fields crops, which makes up the majority of irrigated land in the Imperial Valley, are salt tolerant. Little or no drop in crop yield would occur if the salinity of the irrigation water were doubled (EC_s = 4.0 dS/m) for most of the field crops. Alfalfa is the exception with an estimated 15 percent reduction in relative crop yield. Garden crops are generally more salt sensitive than the field crops. The decrease in relative crop yield for a doubling of irrigation water salinity would range for zero in the cases of cantaloupes, cauliflower, and watermelon, to more than 40 percent in the cases of carrots and onions.

Sodium and Chloride Toxicity

Sodium and chloride are two major ions that can cause plant damage if they accumulate in the leaves either by root absorption or direct contact via spray irrigation.

Generally, however, sodium and chloride toxicity is limited to tree and vine crops or where saline water is used in spray irrigation. Toxic effects include leaf burn, scorch, and dead tissue along leaf edges. Avocado, citrus, and stone fruits are the most sensitive being susceptible to injury with soil water sodium or chloride concentrations as low as 5 meq/L (115 mg/L) if spray irrigated during the daytime. The relative susceptibility of crops to leaf damage by sodium or chloride toxicity is summarized in Table 10. In the case of sodium when spray irrigation is not used, then the sodium concentration can be as high as 20 meq/L without plant damage or reduction in crop yield.

Boron Toxicity

Boron can be toxic to plants when in excess of that needed for optimum growth. Toxicity effects are evident first as leaf drying at the tips and edges. Boron tolerance varies with soil and crop variety. The relative susceptibility of crops to leaf damage by boron toxicity is summarized in Table 11.

Effects of Sodium Absorption Ration (SAR) on Agricultural Crops

If the exchangeable sodium content on soil is excessive, it can cause clayey soils to swell. As a result, the soil becomes less permeable, hindering or preventing soil leaching to remove salts. Poor aeration and physically poor soil conditions can also result reducing plant growth. The most common index for assessing whether excessive buildup of exchangeable sodium will occur is the sodium adsorption ratio (SAR). The SAR is defined as:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

where *Na*, *Ca*, and *Mg* are the concentrations of sodium, calcium, and magnesium, respectively, expressed in meq/L.

The SAR, coupled with the overall salinity, is used to determine the suitability of water for irrigation in terms of its potential to decrease permeability due to excess sodium buildup in the soil. Water quality guidelines for SAR are presented in Table 12. The SAR of Alamo River water is 6.9 (EC = 3.5 dS/m) and for the Colorado River water, the SAR is 3.2 (EC = 1.2 dS/m).

Suggested Water Quality Objectives for Agricultural Drainage Reuse

One of the most important considerations in assessing the efficacy of a specific agricultural drainage water reuse plan is the potential impact that reclaimed water may have on the crop yield. Therefore, minimum criteria for agricultural drainage water reuse must be based on the premise that the reuse strategy must not affect crop yields significantly in the Imperial Valley (see Table 9). The principal parameters of concern will be salinity (EC), sodium and chloride concentrations, and the SAR. Suggested guidelines for acceptable water quality are proposed in Table 13.

A comparison of the values presented in Table 13 with Colorado River and Alamo River waters are given in Table 14. As can be seen, with the exception of SAR, the Alamo River water does not meet the suggested water quality criteria guidelines for irrigation in the Imperial Valley. Its salinity, boron, sodium, and chloride must be reduced to acceptable levels before it can be used directly for field irrigation.

Task 3. Identification of Agricultural Reuse Alternatives in the Imperial Valley

The concept of reusing agricultural drainage water is not a new one (Walker, 1978; Knapp and Dinar, 1984). Suggested reuse applications include cooling water supply, potable water supply, and irrigation water supply. To date, however, large-scale agricultural drainage water reuse has not been practiced. The only major engineered system involving agricultural drainage water is the Yuma Desalting Plant (YDP), which is operated by the U.S. Bureau of Reclamation. The YDP can produce 60 MGD (68,500 acre-feet per year) of low TDS water by utilizing a conventional water treatment plant (coagulation-softening, sedimentation, filtration) followed by spiral-wound cellulose acetate reverse osmosis (RO) systems. The TDS is reduced from 3,200 mg/L to 100 mg/L through the RO water. Final product water, which includes partially treated water that bypasses the RO system, has a TDS of 300 mg/L. However, the YDP only operates when the TDS of the Colorado River is expected to exceed a TDS limit established by a U.S.-Mexico treaty. When the YDP operates, the final product water is discharged directly into the Colorado River to lower the overall TDS of the water to meet the treaty salinity limit. Brine generated from the process is sent via pipeline to the Santa Clara Marsh in Baja California, which empties into the Gulf of California. To date, YDP has not operated for more than a few months during its existence.

In considering various reuse strategies for agricultural drainage water for this study, the primary consideration was how much the salt load could be increased without being significantly detrimental to crop yields. Two alternatives have been identified for consideration, both of which provide up to 300,000 acre-feet of reclaimed water from the Alamo River for agricultural irrigation reuse.

Summary of Task 3 Outcomes

Two alternatives have been identified for consideration, both of which provide up to 300,000 acre-feet of reclaimed water from the Alamo River for agricultural irrigation reuse:

- Alternative A involves the reuse of agricultural drainage water with no desalinization treatment. Water would be extracted from the Alamo River near its mouth at the Salton Sea (Elevation = -227 ft MSL) and pumped back to Drop 1 of the All-American Canal (Elevation = ~150 ft MSL) or near the initial distribution point in the IID irrigation canal network depending on the location of potable water diversions. The agricultural drainage reuse water would be blended with normal irrigation water from the Colorado River. See Figure 4 for location of Drop 1.

- Alternative B involves reuse of agricultural drainage water after treatment to remove salinity by RO treatment (and necessary pretreatment processes to ensure effective RO treatment.) Treated water could be distributed directly from the treatment plant to the irrigation fields since this water will meet the suggested water quality criteria directly. Existing IID irrigation canals could be used for distribution as well; however, some type of conveyance system would be needed to carry the water to the initial distribution point(s).

A preliminary technical assessment of the two alternatives is presented in Chapter 3, Task 6, Preliminary Evaluation of Reclaiming Agricultural Drainage Waters for Reuse.

Task 4. Pretreatment Process Assessment – Alternative B

Task 4 outcomes are presented in separate subsections. Bench-scale testing results include those from 1) Imhoff cone tests, 2) jar testing, 3) conventional treatment bench-scale testing, 4) selective calcium treatment bench-scale testing, and 5) bench-scale membrane (MF/UF) filtration testing.

Summary of Task 4 Outcomes

- Imhoff cone tests provided a semi-quantitative assessment that plain sedimentation would be insufficient as a pretreatment process for RO application.

- Jar testing confirmed that alum, ferric chloride, and selective lime softening were found to be effective coagulants.

- Conventional treatment bench-scale testing using alum or ferric chloride as coagulant followed by dual-media filtration consistently produced an effluent water having turbidities (NTU) ≤ 0.6 and silt density index (SDI) ≤ 3.4.

- Selective calcium treatment bench-scale testing using ferric chloride as coagulant followed by dual-media filtration consistently produced an effluent water having turbidities (NTU) ≤ 0.4 and silt density index (SDI) ≤ 3.3.

- Bench-scale membrane (MF/UF) filtration testing produced an effluent water having turbidities (NTU) ≤ 0.50 and silt density index (SDI) ≤ 4.0.

Imhoff Cone Tests

Imhoff cone tests provided a semi-quantitative assessment of the settleability of Alamo River suspended solids without coagulant addition (plain sedimentation). Results comparing raw and plain settled Alamo River water are summarized in Table 15. A significant fraction of the suspended solids in the Alamo River settle readily. However, plain sedimentation, even for 24 hours, would be insufficient as a pretreatment process for RO application.

Jar Testing

To evaluate the potential effectiveness of conventional water treatment with alum and ferric chloride coagulants, and selective calcium lime-soda ash softening, a series of jar tests were performed. Results of these tests are discussed in this section.

Conventional Treatment with Alum Coagulant

Using a common Alamo River sample, jar tests were performed using alum doses of 0, 5, 10, 20, 30, and 50 mg/L at average G values of 20, 40, and 60 s^{-1}. Results of those jar tests are presented in Figure 6.

Based on the results of these jar tests, an optimum alum dose between 20 and 30 mg/L was determined at G values of 40 and 60 s^{-1}. Supernatant turbidities of less than 1.0 NTU were achieved. Higher alum doses were required at a G value of 20 s^{-1} to achieve similar supernatant turbidity. Thus, for alum, a G value of 40 s^{-1} was established as the standard velocity gradient for all subsequent alum jar testing and for the continuous-flow bench-scale conventional treatment system tests using alum as the coagulant.

Prior to the start of an experimental run with the bench-scale continuous-flow conventional treatment system, a jar test was performed to determine the optimum coagulant dose at a G value of 40 s^{-1}. Results of the jar tests for the alum experimental runs are presented in Figure 7. Optimum alum doses were found to be relatively consistent, around 30 mg/L, between test runs and different Alamo River samples.

During the temperature effects jar testing, some differences were observed between the different temperatures (see Figure 8). The optimum alum dose was found to be closer to 20 mg/L at both 21^{o}C and 31^{o}C whereas, at the colder temperature, the optimum dosage was found to be 30 mg/L. These results are consistent with slower chemical and flocculation kinetics at colder temperatures. However, the differences observed are well within the variation of water quality for the sub-samples. Replicate testing with a much larger sample set would be required to refine the optimum dosages further for the various temperatures.

Conventional Treatment with Ferric Chloride Coagulant

Using a common Alamo River sample, an initial set of jar tests was performed using ferric chloride doses of 0, 0.5, 1, 2, 5, and 10 mg/L at average G values of 20, 40, and 60 s^{-1}. Results of these initial jar tests are presented in Figure 9.

Based on the results of these jar tests, an optimum ferric chloride dose between 10 and 20 mg/L was determined at G values of 40 and 60 s^{-1}. Supernatant turbidities of about 1.0 NTU were achieved. Similar low turbidities were not achieved at a G value of 20 s^{-1}. Thus, for $FeCl_3$, a G value of 40 s^{-1} was established as the standard velocity gradient for all subsequent $FeCl_3$ jar testing and for the continuous-flow bench-scale conventional treatment system tests using $FeCl_3$ as the coagulant.

Prior to the start of an experimental run with the bench-scale continuous-flow conventional treatment system, a jar test was performed at G = 40 s^{-1} to determine the optimum coagulant dose. Results of the jar tests for the $FeCl_3$ experimental runs are presented in Figure 10. Optimum $FeCl_3$ doses were found to be between somewhat higher, but still 10 to 20 mg/L, for the various test runs and different Alamo River samples compared to initial jar test results. For the bench-scale continuous-flow conventional treatment system a dose of 20 mg/L was used for all runs with $FeCl_3$.

During the temperature effects jar testing, some differences were observed between the different temperatures (see Figure 11). The optimum $FeCl_3$ dose was found to be closer to 10 mg/L at both 12^{o}C and 21^{o}C. At the warmer temperature, the optimum dosage was closer to 20 mg/L. These results are inconsistent with the expected trend of lower optimum coagulant dose at higher temperatures due to faster chemical and flocculation kinetics at warmer temperatures. However, the differences observed are well within the variation of water quality for the sub-samples. Replicate testing with a much larger sample set would be required to refine the optimum dosages further for the various temperatures.

Selective Calcium Treatment with $FeCl_3$ Coagulant

Using a common Alamo River sample, jar tests were performed using selective calcium softening at the stoichiometric amounts for lime and soda ash, and ferric chloride doses of 0, 1, 2, 5, 10, and 20 mg/L at average G values of 20, 40, and 60 s^{-1}. Results of those jar tests are presented in Figure 12.

Based on the results of these jar tests, a G value of 20 s^{-1} was observed to be too low to achieve acceptable effluent turbidity. This effect was possibly due to the kinetics of lime dissolution. Lime is added to the water in slurry form and must dissolve to react properly. The one minute rapid-mix period at G = 600 s^{-1} was most likely insufficient for complete dissolution and reaction to occur. Further dissolution and reaction occurred during the flocculation steps. Higher G values provided more power for better dissolution, promoting faster reaction kinetics. Thus, the highest G value of 60 s^{-1} achieved the best results. Poor dissolution of the lime at the lower G values resulted in higher turbidity and incomplete reaction. Additional evidence for this hypothesis can be obtained by reviewing the final pH values from the jar tests (see Figure 13). Lower dissolution of lime results in lower pH values. As seen in Figure 13, higher G values produced higher final pH values. Final pH values of around 10 were expected from the selective calcium treatment. The addition of ferric chloride results in lower final pH values because of its acid properties. This effect is seen for G equals 40 and 60 s^{-1}. On the basis of the jar testing for selective calcium treatment, an average G value of 60 s^{-1} and a ferric chloride dose of 5 mg/L were determined to be optimum parameters.

Temperature effect studies for softening treatment were conducted similar to the coagulant jar tests. After allowing sub-samples to equilibrate overnight in warm and cold incubators, jar tests were performed on the temperature modified water samples. These jar tests were performed at room temperature using an average G value of 60 s^{-1} and selective lime treatment with supplementary ferric chloride coagulant. Final measured temperatures of 31^{o}C and 12^{o}C were used for identification purposes. Results of the temperature effect jar tests are presented in Figure 14.

Similar to what was observed with G value, at the lower temperature incomplete lime dissolution was experienced, resulting in poorer turbidity removal and lower final pH readings. At lower temperatures, the water has higher viscosity and reaction rates are reduced. Higher G values and/or longer contact times may be required at lower temperatures to compensate.

Prior to the start of an experimental run with the bench-scale continuous-flow softening treatment system, a jar test was performed to determine the optimum coagulant dose. Results of the jar tests for the ferric chloride experimental runs are presented in Figure 15. Optimum ferric chloride doses were found to be between 5 and 20 mg/L, between test runs and different Alamo River samples. Note that the results from Run 5 vary from the other two runs. During Run 5, the jar test was improperly run at G_{avg} = 40 s^{-1}, instead of the specified value of 60 s^{-1}. The CFS system, however, was operated at G_{avg} = 60 s^{-1} for Run 5.

Unfortunately, most of the samples from the series of jar tests evaluating optimum ferric chloride dosage, G value, and temperature effects studies were inadvertently discarded before hardness measurements were made. Only one sample, G = 20 s^{-1}, T = 21^{o}C, $FeCl_3$ = 20 mg/L was saved and hardness analyzed. For that sample, total hardness (TH) was reduced from 18.6 meq/L to 12.4 meq/L, a 33 percent reduction. Calcium hardness (CH) was reduced from 9.1 meq/L to 3.0 meq/L, a 67 percent. The level of calcium hardness removed in this sample was substantially less than expected, 93 percent. As noted earlier, incomplete dissolution of lime occurred, affecting the calcium removal process. However, 67 percent calcium removal is higher than the 45 percent removal required to prevent gypsite formation potential in the RO reject stream.

Hardness removal was also monitored during the jar testing for the CFS softening runs. Average reduction of TH was 37 percent, from 17.5 to 11.0 meq/L. Average reduction of CH was 58 percent, from 9.3 meq/L to 3.9 meq/L.

Conventional Treatment Bench-Scale Testing

A series of bench-scale tests were carried out to evaluate the potential effectiveness of conventional water treatment with alum and ferric chloride coagulants. Results of these tests are discussed in this section.

Conventional Treatment with Alum Coagulant

One of the most common coagulants is Alum [$Al_2(SO_4)_3$-$18H_2O$] whose effective pH range is approximately 4.5 to 8.0 (Reynolds and Richards, 1995). The insoluble aluminum hydroxide, which forms when alum reacts with calcium bicarbonate in the water, produces a gelatinous floc that sweeps out the suspended particles as it settles in the sedimentation tank.

Coagulation, Flocculation, and Sedimentation (CFS)

CFS effluent characteristics were averaged to form composite values for the three effluent grab samples taken during a run. Average composite effluent characteristics from the CFS system for alum coagulants are summarized in Table 16. Variation of tested water quality parameter values was generally less than 10 percent between the three grab samples for a given test run (see Figure 16).

SDI tests were conducted to determine whether CFS treatment alone could be sufficient for RO pretreatment. However, during the initial experimental run with alum it was found that the SDI values was 14.6, much greater than 5. For this reason, further SDI analyses of the CFS effluents were not conducted and are not reported.

Confirming the jar test results, alum was found to be effective coagulants in the bench-scale CFS system. About 96 percent reduction of TSS and turbidity was achieved. The average effluent concentration was 10.7 mg/L and the average effluent turbidity was 3.3 NTU.

Dual-Media Filtration (DMF)

Variation of parameter values was generally less than 10 percent between the grab samples for a given test run (see Figure 17). Thus, DMF effluent characteristics were averaged to form composite values for the effluent grab samples taken during a run. Average composite effluent characteristics from the DMF system for alum coagulant are summarized in

Table 17. Although measured, pH and EC measurements are not presented in these tables. Within the variability of the analyses, these parameters were found to be the same as those measured in the CFS (see Table 16) effluent.

The quality effluent from the DMF filters when alum was used was found to be excellent. Effluent turbidities were between about 0.40 and 0.60 NTU. Slightly higher TSS and turbidities were observed at the highest filtration rate, 6 gpm/ft^2.

During the DMF filter runs the applied head, measured as water level above the media, was monitored with time. Plots of applied head versus filtration time for runs with alum are presented in Figure 18. As can be seen the rate of headloss was generally linear during these limited filtration runs. Average DMF headloss rates for alum coagulation are summarized in Table 18.

Conventional Treatment with Ferric Chloride Coagulant

Another common coagulant is ferric chloride [$FeCl_3$] whose operating range lies between pH 4 and pH 12. The ferric chloride reacts with natural bicarbonate alkalinity to form ferric hydroxide and the floc that forms is generally a dense and settles rapidly during sedimentation.

Coagulation, Flocculation, and Sedimentation (CFS)

CFS effluent characteristics were averaged to form composite values for the three effluent grab samples taken during a run. Average composite effluent characteristics from the CFS system for ferric chloride coagulant are summarized in Table 19. Variation of tested water quality parameter values was generally less than 10 percent between the three grab samples for a given test run (see Figure 16).

Silt density index (SDI) tests were conducted to determine whether CFS treatment alone could be sufficient for RO pretreatment. However, during the initial experimental run with ferric chloride it was found that the SDI values was 10.2, much greater than 5. For this reason, further SDI analyses of the CFS effluents were not conducted and are not reported.
Confirming the jar test results, ferric chloride was found to be effective coagulants in the bench-scale CFS system. About 97 percent reduction of TSS and turbidity was achieved. When ferric chloride was used the effluent suspended solids and turbidity values were 7.8 mg/L and 2.3 NTU, respectively.

Dual-Media Filtration (DMF)

Variation of parameter values was generally less than 10 percent between the grab samples for a given test run (see Figure 17). Thus, DMF effluent characteristics were averaged to form composite values for the effluent grab samples taken during a run. Average composite effluent characteristics from the DMF system for ferric chloride coagulant are summarized in Table 20. Although measured, pH and EC measurements are not presented in these tables.

Within the variability of the analyses, these parameters were found to be the same as those measured in the CFS effluent (see Table 19).

The quality effluent from the DMF filters when ferric chloride was used was found to be excellent. Effluent turbidities were between 0.43 and 0.49 NTU. The highest turbidity was observed at the highest filtration rate, 6 gpm/ft^2.

During the DMF filter runs the applied head, measured as water level above the media, was monitored with time. Plots of applied head versus filtration time for runs with ferric chloride are presented in Figure 18. As can be seen the rate of headloss was generally linear during these limited filtration runs. Average DMF headloss rates for ferric chloride coagulation are summarized in Table 18.

Selective Calcium Treatment Bench-Scale Testing

Bench-scale continuous-flow testing was performed to simulate the operation of a full-scale selective calcium softening treatment system used as a pretreatment step for RO desalination. The same system that was employed for conventional treatment with alum and ferric chloride coagulation was used for selective calcium softening treatment, the CFS and DMF units. One difference in operation from when alum and ferric chloride coagulation was tested was that lime slurry and soda ash solution was also added to the rapid mix chamber at a dosage rate of 175 mg/L and 240 mg/L, respectively. In addition, to prevent cementation of the DMF units, the pH of the CFS effluent was adjusted to between 7 and 8 by the addition of technical grade concentrated sulfuric acid.

The stoichiometric dosages for lime and soda ash additions for selected calcium softening were calculated and summarized in Table 21. The maximum limit for calcium removal is down to 12 mg/L as calcium (93 percent removal). In practice higher calcium concentrations will result because of kinetic considerations and the presence of other ionic species. Even with selective calcium treatment, acid will still be needed for calcite formation prevention, however to different pH values. If 45 percent calcium removal were achieved, then a pH of 6.7 or less would be required. If 90 percent calcium removal were achieved, then a pH of 7.5 or less would be required.

Coagulation, Flocculation, and Sedimentation (CFS) - Lime Softening

Variation of parameter values was generally less than 20 percent between the three grab samples for a given test run (see Figure 19). Thus, CFS effluent characteristics were averaged to form composite values for the three effluent grab samples taken during a run. Average composite effluent characteristics from the CFS system for the selective calcium softening runs are summarized in Table 22. About 94 percent reduction of TSS and turbidity was achieved. Compared to alum and ferric chloride coagulation, the CFS effluent from selective calcium softening was slightly lower were in terms of turbidity and TSS.

SDI tests were conducted to determine whether CFS treatment alone could be sufficient for RO pretreatment. However, during the initial experimental run with selective calcium softening and ferric chloride coagulant it was found that the SDI values was 17.8, much greater than 5. For this reason, further SDI analyses of the CFS effluents were not conducted and are not reported.

Dual-Media Filtration (DMF) - Lime Softening

Variation of parameter values was generally less than 10 percent between the grab samples for a given test run (see Figure 20). Thus, DMF effluent characteristics were averaged to form composite values for the effluent grab samples taken during a run. Average composite effluent characteristics from the DMF system for the selective calcium softening runs are summarized in Table 23. Although measured, EC measurements are not presented in these tables. Within the variability of the analyses, these parameters were found to be the same as those measured in the CFS effluent.

The quality of the effluent from the DMF filters, when selective calcium softening was employed, was found to be excellent and similar in quality to the alum and ferric chloride coagulation. Effluent turbidities were between 0.30 and 0.40 NTU at all three filtration rates tested. The average SDI of the DMF effluent was 3.3, which is comparable to that achieved for both alum and ferric chloride coagulation. Overall, the effluent from the selective calcium softening treatment produced acceptable RO feed water, less than 1 NTU and SDI less than 5.

Average hardness reductions achieved through the continuous-flow selective calcium-softening process closely matched the results of the jar tests conducted to determine optimum ferric chloride dose for the experimental runs. TH reduction was 40 percent, from 16.9 to 11.0 meq/L. Average reduction of CH was 57 percent, from 9.0 meq/L to 3.9 meq/L.

During the DMF filter runs the applied head, measured as water level above the media, was monitored with time. Plots of applied head versus filtration time for runs with alum and ferric chloride are presented in Figure 21. As can be seen the rate of headloss was generally linear during these limited filtration runs. Average DMF headloss rates are summarized in Table 24. Headloss rates in the DMFs following selective calcium softening treatment were much slower than that experienced with conventional alum or ferric chloride coagulation alone.

Bench-Scale Membrane (MF/UF) Filtration Testing

The objective of this part of the study was to assess MF and UF as an alternative to conventional water treatment processes for RO pretreatment. Specifically, the goals were to ascertain expected treatment performance of MF and UF modules using either raw or settled Alamo River water as influent and to study the effects of TMP on permeate flux rate. Analyses of permeate flux and particle rejection in MF/UF is essential for evaluating the efficacy of subsequent membrane desalination treatment step using low-pressure reverse osmosis (LPRO). The evaluation of irreversible membrane fouling and long-term membrane degradation, which will ultimately affect the efficiency and cost of subsequent membrane desalination, was not included in this part of the study. Membrane fouling and long-term effects are to be addressed in a subsequent project.

Bench-scale testing was carried out using 1) a stirred-cell-apparatus and 2) continuous flow test units using agricultural drainage water from Alamo River as feed.

Stirred-Cell Apparatus Testing

Permeate flux experiments using UF membranes were carried out using a stirred-cell apparatus to determine the flux behavior at increasing influent concentrations and transmembrane pressures. Results for membrane filtrate flux and effectiveness of the membrane treatment are presented separately in the following sections

Filtrate Flux

Permeate flux was measured for a clean water feed, as well as for Alamo River feed waters. The flux-TMP relationship for clean membranes can be represented by R_m, which is the intrinsic membrane resistance, [kPa-d-m^{-1}]. The value of R_m is determined using flux data generated using a new membrane and high purity water, e.g. clean water flux. The clean water flux versus TMP data follows Darcy's law. R_m is then defined to be equal to the inverse slope of the regression line fitted to the flux versus pressure data. A plot of the clean water flux data for YM10 and ZM500 membranes is found in Figure 22.

The difference in clean water flux between the two membranes, YM10 and ZM500, is considerable, two orders of magnitude, and is attributed to the difference in membrane pore size. However, the effectiveness of a membrane as a barrier is also a function of the surface properties of both the membrane and the particulate material in the feed. A summary of flat-sheet MF membrane characteristics is found in Table 25.

To evaluate the effectiveness of MF/UF as pretreatment to RO both raw and settled-raw Alamo River water was used as influent to the stirred-cell membrane apparatus. The steady state permeate flux values at each pressure condition was averaged and plotted versus TMP for the ZM500 and YM10 flat sheet MF/UF membrane filters. Plots of average permeate flux versus TMP for experiments conducted with raw and settled-raw Alamo River influent are presented in Figure 23.

Permeate flux increased in experiments conducted with YM10 membrane filter as the TMP was increased in a stepwise fashion from 10 to 30 psi (69 to 207 kPa). However, no further increase in flux was observed at higher transmembrane pressures, 40 and 50 psi (276 and 345 kPa). Limiting permeate flux was attained at approximately 30 psi (210 kPa) which corresponds to the highest transmembrane pressure usually specified for hollow fiber MF cartridge filters.

Permeate flux decreased in experiments conducted with ZM500 membrane filter as the TMP was increased in a stepwise fashion from 10 to 50 psi (69 to 345 kPa). Permeate flux decline was close to linear for both raw and settled-raw Alamo River water influent and did not attain a limiting flux condition. In general, fouling is more likely to occur under conditions of high influent concentrations and low hydraulic turbulence. Furthermore, membrane pore plugging, due to the size difference between membrane pores and particles in the feed water, is expected for those membranes where pore size is larger than influent particles.

Strong electrostatic and van der Waals interaction forces between particle and membrane pore walls, reversibly or irreversibly, retain constituents that are introduced into the membrane matrix. Thus, decreasing permeate flux with higher TMP is observed for membrane having relatively large pore sizes due to membrane pore plugging, which is typical for microfiltration of high turbidity natural waters. Conversely, an increasing permeate flux with higher TMP is observed when the relative membrane pore size is small compared to the particulate material in the feed water. Also, a limiting permeate flux condition is observed for the latter case due to the build-up of rejected particulate material at the membrane surface, a phenomena which typifies ultra filtration.

Removal Efficiencies

Because MF/UF are barrier technologies, removal of particulate species is almost always close to 100% for a properly designed system where the membrane pore size is matched by the particle size(s) in the influent. Results comparing raw and settled raw Alamo River water before and after MF/UF membrane filtration are summarized in Table 26.

After plain sedimentation the TSS concentration is reduced on average by 64 percent and the turbidity by about 40 percent. This removal efficiency is not sufficient for pretreatment of RO feed. Results comparing water quality after MF/UF appear to be similar irrespective of the MF/UF membrane used in the experiment. Both YM10 and the ZM500 membranes were found to be effective particle barriers. More than 99 percent reduction of turbidity was achieved for both raw and settled raw Alamo River used as feed waters. Based on turbidity and TSS, both membranes are deemed equivalent in terms of removal characteristics. However, turbidity and TSS cannot be used to discriminate between tested membranes.

Continuous-Flow Re-Circulating MF/UF System (CFMF)

Settled-raw and raw Alamo River water were tested with two different MF membranes in a re-circulating flow membrane filter apparatus (CFMF). Results for CFMF membrane permeate flux and the removal effectiveness of the membrane treatment are presented separately in the following sections.

Permeate Flux

After collection and transport to UCR, Alamo River water was allowed to settle overnight and supernatant transferred to the feed tank (Figure 2). This water is designated as settled-raw Alamo River water. Steady state permeate flux values at the pre-selected TMP conditions were obtained at a cross-flow rate of 0.12 L/s. Plots of permeate flux versus TMP for the experiments conducted with settled-raw Alamo River water using PM500 and PMF0.1 membranes are presented in Figures 24 and 25, respectively.

Permeate flux increased with pressure in all cases. Average flux data did not diverge significantly from linear behavior for the range of TMPs tested due to little or no build-up of rejected particulates at the membrane surface in combination with adequate fluid shear at the membrane surface. Limiting permeate flux could not be achieved due to the operational constraints of manufacturer specified maximum pressures and the selected pressure differential along the membrane cartridge, 5 psi.

Permeate flux was approximately 10 to 15 percent higher for the PMF0.1 membrane compared to the PM500 membrane. Permeate flux increased only slightly or not at all with TMP and a near limiting flux was approached for TMP's exceeding 17.5 psi. The somewhat greater variability between test runs was probably due to a combination of reversible and irreversible fouling.

For the experiments conducted with raw Alamo River water the barrel contents were violently agitated using an air sparger before and during transfer to the feed tank. Steady state permeate flux values at the pre-selected TMP conditions were obtained at a cross-flow rate of 0.12 L/s. Plots of permeate flux versus TMP for the experiments conducted with raw Alamo River water are presented in Figures 26 and 27 for the PM500 and PMF0.1 membranes, respectively.

Permeate flux increase with TMP in experiments conducted at the higher suspended solids concentrations associated with the raw Alamo River water was minimal. The permeate flux was relatively constant at all TMPs tested. Limiting permeate flux occurs due to build-up of particulate materials at the membrane surface. A combination of TMP and low hydraulic shear appear to affect the PMF0.1 membrane more than the PM500 membrane. Similar to the experiments using settled-raw Alamo River water as feed, average permeate flux was approximately 10 to 15 percent higher for the PMF0.1 membrane compared to the PM500 membrane.

The suspended solids concentration in raw Alamo River water is approximately three times the concentration of settled-raw Alamo River water (see Table 26). The downward shift observed for the PM500 membrane at the maximum TMP is hypothesized to be due to partial clogging of the entrant section of the hollow fibers at the inlet to the cartridge rather than irreversible fouling of the membrane itself. A strainer, equipped with a 20 mesh stainless steel screen, was added to the influent line to prevent materials larger than the inside diameter of the hollow fibers to block the flow.

Pretreatment of Alamo River water using plain sedimentation increases the range of possible operating conditions. Operation in excess of the pressure necessary to achieve limiting permeate flux can result in an increase in particle permeation through the membrane pores, irreversible membrane fouling and subsequent higher operational cost. Also, the allowable

TMP range is larger, for which an optimum operational condition based on permeate quality and energy usage can be sought after, when particle concentration in the feed water is low.

Removal Efficiencies

Two different influent feed waters were tested – raw and settled-raw Alamo River water. Both feed waters exhibited comparable effluent qualities after MF. Measured average raw and settled raw Alamo River water quality parameters and effluent water quality after CFMF are summarized in Table 27.

Effluent water qualities after microfiltration are comparable for both raw and settled-raw influent, which supports the observation that MF is an absolute barrier to particulate materials. Also, treated water (MF) is within the suggested water quality criteria for RO treatment, e.g. turbidity less than 1.0 NTU, and SDI <5. Based on these results MF is an effective pretreatment method for solids removal prior to subsequent desalination using RO treatment. Effective performance is achieved for either raw or settled-raw Alamo River water.

Suspended Solids and Particle Size Distribution

Conventional treated water after dual media filtration (DMF) and continuous-flow microfiltration (CFMF) treatments are compared in Table 28. There is little or no significant difference between the two treatments, with microfiltration (CFMF) data exhibiting somewhat less variability between experiments. Both treatments, DMF and CFMF, are within the suggested water quality criteria for RO treatment.

Detailed particle size distribution (PSD) data are also indicators for potential fouling of pretreated water. Their analysis is an effective way to compare the particulate composition between different feed waters. Even if the interpretation is hampered by the lack of standardized data reduction methods, the presence of particles in certain size ranges may be indicative to potential fouling problems during long-term operation. Successive particle removal is illustrated in Figure 28, starting with raw Alamo River water followed by plain sedimentation (settled-raw), conventional treatment using ferric chloride and alum, respectively, after DMF, and CFMF. As can be seen, there is significant particle removal at the various size ranges. Overall, as expected, DMF and MF had the lowest particle counts at all the size ranges tested. In Figure 29, the particle size distribution of particulates from CFMF and DMF are compared.

Task 5. Salinity Removal by Reverse Osmosis – Alternative B

Pre-treated waters from the continuous-flow bench-scale testing unit (CFS/DMF) and continuous-flow re-circulating MF/UF System (CFMF) were tested with two different RO membranes in a recirculating flow flat-sheet membrane apparatus. Desalination effectiveness was assessed in terms of electroconductivity (EC) and total dissolved solids (TDS). In addition, to qualitatively assess the short-term effectiveness of the different pretreatment schemes to minimize scaling and fouling, the RO membranes were examined by scanning electron microscopy (SEM) for scaling and fouling at the surface.

Results for RO membrane permeate flux and salt rejections are presented in separate sections below. So far two different RO membranes, ESPA and LFC1 (Hydronautics, USA) have been tested. The results presented here are limited to short-term experiments in order to assess the technical feasibility for membrane desalination. Subsequent work will address long-term performance of RO membranes as a function of different pre-treatment strategies.

Summary of Task 5 Outcomes

- Approximately 99 percent of major cations are removed but with the sodium removal being approximately 95 percent.

Permeate Flux

Clean water flux measurements as a function of pressure were conducted and the resulting mass transfer coefficients (MTC) for the two membranes tested are shown in Figure 22. Even though clean water flux has limited value in terms of predicting permeate flux and fouling characteristics, the measurements provide an upper operational bound and serves as a baseline for hydraulic properties of the virgin RO membrane.

CFMF treated Alamo River water and Alamo River water treated by conventional treatment with DMF were used as influent to the RO flat sheet test-cells. In this work no distinction has been made between conventionally treated water using alum, ferric chloride, or lime softening, as the effluent quality in terms of turbidity and SDI were nearly equal. Similarly, no distinction between CFMF treated settled-raw and raw Alamo River water was made, as effluent water qualities are indistinguishable.

The steady state permeate flux values at each pressure condition were averaged and plotted versus TMP. Plots of measured average permeate flux versus TMP for experiments conducted with CFMF feed waters and ESPA and LFCI membranes are presented in Figure 30. Plots of measured average permeate flux versus TMP for experiments conducted with DMF feed water and ESPA and LFCI membranes are presented in Figure 31. The experiments conducted in this study were of relatively short duration so that membrane fouling or scaling is not expected to occur. Hence, the reported flux data represent the flux expected of new membranes with pretreated waters used as influent.

Removal Efficiencies

Measured cation concentrations in the finished waters were nearly identical for all pretreatment approaches. Thus, the results for all pretreatment schemes for a single membrane were averaged. Final cation concentrations and percent removal by RO treatment using ESPA and LFCI membranes are found in Table 29. There is no appreciable difference of removal efficiency for cations between the two membranes tested. Approximately 99 percent of major cations are removed, with the sodium removal rate being somewhat lower at approximately 95 percent.

Microscopic Analysis

A microscopic analysis of an RO membrane was performed using a scanning electron microscope (SEM) equipped with an energy-dispersive x-ray analysis (EDAX) EDS spectrometer with Si/Li detector for collecting images and x-ray spectra. The composition of the material was determined on a microscopic scale with relative accuracy of 1 to 3 percent for elements with Z>9. An analysis of a clean ESPA membrane surface is shown in Figure 32. The peaks are from left to right carbon, oxygen, copper, sodium, magnesium, phosphorus, sulfur, and calcium, which are all the elements expected to be retained by the membrane or are part of the membrane itself. A second analysis of an ESPA membrane surface where the feed water was pre-treated water using conventional water treatment with ferric chloride as the coagulant is shown in Figure 33. As indicated by the EDAX scan, this membrane has a buildup of calcium, silicon, as well as iron. Aluminum and silicon are most likely from clay particles that escape the pretreatment processes and the iron is probably from the coagulant used in the pre-treatment. Calcium may also be present from the clay particles, but more likely, the calcium is from precipitation. In these experiments, pH was not adjusted to 6 to prevent calcium carbonate precipitation. SEM/EDAX analysis will be used in subsequent work to analyze retained elements that accumulate on the membrane surface after long times.

Task 6. Preliminary Evaluation of Reclaiming Agricultural Drainage Waters for Reuse

Two alternatives have been identified for consideration, both of which provide up to 300,000 acre-feet of reclaimed water from the Alamo River for agricultural irrigation reuse. Both alternatives satisfy the criteria for water reuse, namely sufficient water volumes, adequate water quality for maintaining crop yields, and the availability of commercially available treatment technologies to achieve the desired treatment goals.

Summary of Task 6 Outcomes

- Alternative A involves the reuse of agricultural drainage water with no desalinization treatment. Water would by extracted from the Alamo River near its mouth at the Salton Sea (Elevation = -227 ft MSL) and pumped back to the vicinity of Drop 1 of the All-American Canal (Elevation = ~150 ft MSL) or near the initial distribution point in the IID irrigation canal network. Refer to Figure 4 for site location of Drop 1.

- Alternative B involves reuse of agricultural drainage water after treatment to remove salinity by RO treatment (and necessary pretreatment processes to ensure effective RO treatment.) Treated water could be distributed more centrally to the treatment plant since this water will meet the suggested water quality criteria directly. Existing IID irrigation canals could be used for distribution; however, some type of conveyance system would be needed to carry the water to the initial distribution point(s).

Alternative A – Reuse of Alamo River Water – No Salinity Removal.

Reuse of water from the Alamo River directly onto nearby fields for irrigation would be possible for some, but not all crops grown in the Imperial Valley. Thus, for Alternative A, it is proposed that up to 300,000 acre-feet per year of water be extracted for reuse from the Alamo River near its mouth at the Salton Sea. Treatment of the water to remove suspended solids and reduce turbidity may be desirable for aesthetic reasons, but not required in terms of the suggested irrigation water quality criteria (Table 13) Water would be conveyed through a system of pump stations and pipelines to the vicinity of Drop 1 of the All-American Canal, just after the Coachella Canal diversion. The overall elevation lift is about 380 ft and the estimated pipeline length is about 75 miles, a significant distance

Estimates of required pipeline size and required pumping heads were conducted assuming a nominal maximum flow velocity of 5 feet per second and the Darcy-Weisbach formula for headloss (McGhee, 1991). The projected required pipe size would be 10 ft (for 300,000 afy) and the total pumping head required is estimated to be approximately 725 ft. (345 ft of headloss and 380 ft of lift). Assuming an overall pump efficiency of 80 percent, the estimated energy requirement for conveyance would be 2.76×10^8 kW-hr/yr, or 920 kW-hr/ac-ft.

With respect to salinity, a schematic of the flow and salt mass load balance is shown in Figure 34 for Alternative A. As shown, it is proposed that up to 300,000 afy of Alamo River reuse water be blended with normal irrigation water from the Colorado River. At maximum reuse, the estimated salinity of the resultant irrigation water blend would be 1,050 mg/L (EC = 1.65), an increase of about 30 percent. Estimated values for the suggested irrigation water quality criteria are summarized in Table 30 for reuse rates of 0.1, 0.2, and 0.3 mafy.

The quality of the blended irrigation water should by acceptable for all crops as long as spray irrigation is not used. For spray irrigation, the sodium concentration would be too high for sensitive plants. However, even with no reuse, the Colorado River water sodium concentration is sufficiently high as to be considered potentially damaging to sodium sensitive crops.

Alternative B - Reuse of Alamo River Water – Salinity Removal to Maintain Constant Salt Mass Loading.

Although increased salinity, up to the projected levels for Alternative A, should have little potential impact on relative crop yield in the Imperial Valley, there will most likely be a reluctance to accept untreated water for reuse, especially if there is no economic incentive to the agricultural community. Therefore, for Alternative B it is proposed that a RO treatment system be developed to generate a reclaimed water flow, up to 300,000 afy, which is similar in salinity level to that of the existing Colorado River water (EC = 1.2 dS/m). Water would be first be extracted from the Alamo River and conveyed to a treatment site adjacent to the Alamo River near the Salton Sea. Treated water could be conveyed to any location in the IID irrigation canal system for distribution.

The pH of the pretreated feed will need to be adjusted to 6.1 to minimize calcium scaling. Lime stabilization of the RO permeate, which will have a TDS of about 45 mg/L, will not be required because the permeate will be reblended with bypass water. The resultant product water will have a TDS of 800 mg/L and a pH of 7.0

Based on the calcium and sulfate concentrations of the Alamo River, the net recovery of an RO system would be limited to about 70 percent to prevent $CaSO_4$ scaling. Higher recoveries may be practiced if softening, such as lime-soda ash precipitation, is implemented. Lime-soda ash softening would also be considered an alternative to alum or ferric chloride coagulation for suspended solids and turbidity reduction.

Assuming an RO recovery of 70 percent, approximately 390,000 afy of water would need to be withdrawn from the Alamo River to generate 300,000 afy of product water. The fate of the 87,000 afy of RO concentrate is unknown at this time. A schematic of the flow and salt mass load balance is shown in Figure 35 for Alternative B. A conceptual diagram of the treatment plant for Alternative B is shown in Figure 36. The conceptual design for the RO system was based upon a membrane system software design package (*Winflows*, Version 1.2, developed by Osmonics 1999). Based on a 2:1 array (Osmonics AG8040F elements), the RO system would be have 5,620 housings in the first stage and 2,810 housings in the second state. Each housing has six eight-inch elements. The average flux rate is estimated to be 10.0 gal/ft^2-d with a feed pressure of about 136 lb_f/in^2 (935 kPa).

CHAPTER 4. CONCLUSIONS

The principal conclusions resulting from the evaluation of Alamo River water for agricultural reuse are presented in the following sections.

Task 1. Characterization of Agricultural Drainage Water: Flow and Quality

Approximately 850,000 acre-feet of agricultural drainage flow into New River and Alamo River. Nearly 100 percent of the Alamo River's average annual flow of 600,000 acre-feet is agricultural drainage, while only 57 percent of the New River's average annual flow of 450,000 acre-feet is comprised of agricultural flow.

Imperial Valley agricultural drainage water is brackish. The measured average TDS of the Alamo River is around 2,400 mg/L. The average TDS of Colorado River water used for irrigation is about 820 mg/L, and the agricultural drainage volume is approximately one third of the applied irrigation water. Average water quality data for the Alamo River based on USGS measurements near Calipatria and have remained approximately constant over the last 10 years (see Table 6).

Task 2. Water Quality Objectives for Agricultural Drainage Water Reuse

One of the most important considerations in assessing the efficacy of a specific agricultural drainage water reuse plan is the potential impact that reclaimed water may have on the crop yield. Therefore, minimum criteria for agricultural drainage water reuse must be based on the premise that the reuse strategy must not affect crop yields significantly in the Imperial Valley. The principal parameters of concern will be salinity (EC), sodium and chloride concentrations, and the SAR. Suggested guidelines for acceptable water quality are proposed in Table 13.

A comparison of the values presented in Table 13 with Colorado River and Alamo River waters are given in Table 14. As can be seen, with the exception of SAR, the Alamo River water does not meet the suggested water quality criteria guidelines for irrigation in the Imperial Valley. Thus, water from the Colorado River is needed to reduce salinity, boron, sodium, and chloride to acceptable levels before it can be used directly for field irrigation.

Task 3. Identification of Agricultural Reuse Alternatives in the Imperial Valley

On the basis of minimum reuse criteria developed in Task 2 for agricultural drainage water reuse that will not affect crop yields significantly or decrease crop value per acre, an agricultural drainage water reuse alternative that will provide reclaimed water from the Alamo River for irrigation was formulated. This alternative, designated Alternative A, was developed on the basis of the Alamo River water quality and blending requirements to meet the minimum reuse water quality criteria.

A second reuse alternative was developed on the premise that there may be strong reluctance by the farmers to accept lower quality water caused by agricultural drainage water reuse, even though crop yields and values may be unaffected. A second agricultural drainage water reuse alternative, designated Alternative B, was forwarded on the basis of the Alamo River water quality and the treatment requirements needed to ensure that the delivered reclaimed irrigation water was similar in quality to that of the Colorado River.

A target flow reuse volume of 300,000 acre-feet per year was selected for both alternatives. This volume is approximately 10 percent of the total Colorado River water apportionment to IID.

Task 4. Pretreatment Process Assessment – Alternative B

For RO systems to operate cost effectively and efficiently, pretreatment systems must remove turbidity and suspended solids, reduce the tendency of the water to form scale, and prevent biological slime growth. Fouling reduces permeate flux, or the rate of treated water produced per unit area of RO membrane. A rapid rate of fouling results in increased operation and maintenance costs associated with RO treatment, as well as greater frequency in RO membrane replacement. Two common sources of RO fouling are 1) plugging, or solids buildup, of the membrane surface and 2) precipitate scaling of constituents in the feed water as a result of solute concentration. Thus, in the case of feed water with significant suspended solids concentration and high mineral concentrations, pretreatment of the feed water is required prior to RO desalination.

Based on the data collected to date, conventional water treatment and microfiltration will produce water that is of sufficient quality for RO feed and desalination. Alum and ferric chloride were both found to be effective coagulants. Turbidity values for both coagulants were less than 1.0 NTU and the SDI values were found to be less than 5. Similarly, Alamo River water treated by selective calcium lime-soda ash softening will produce water that is also of sufficient quality for RO feed and desalination. Turbidity was less than 1.0 NTU and the SDI was found to be less than 5.

Overall, MF produced finished water that was slightly better in quality than conventional treatment. The MF effluent had lower TSS, turbidity, and SDI values, and achieved better overall particle removal. Also, greater variability of effluent water quality parameters was exhibited in the treated effluent from the conventional treatment, which may affect the long-term performance of downstream RO treatment. Even so, in terms of pretreatment, both schemes produced water that was sufficient for RO application. Within the scope of this study, the subtle differences between pretreatments did not result in any differences in RO performance.

Long-term studies will be required to ascertain whether these minor differences will impact RO fouling and scaling, and RO performance. The minor performance difference observed between the study alternatives is indicative of their effectiveness for RO pretreatment and the opportunity for agricultural drainage water treatment for reuse purposes.

Task 5. Salinity Removal by Reverse Osmosis – Alternative B

The steady state permeate flux values at each pressure condition were practically equal for conventionally treated water (DMF) and microfiltration (CFMF) water. However permeate flux was approximately two times higher for the ESPA membrane compared with the LFC1 membrane at equal TMP's.

Approximately 99 percent of major cations were removed, with the sodium removal rate being somewhat lower at approximately 95 percent, by RO treatment using ESPA and LFCI membranes. There was no appreciable difference of removal efficiency for cations between he two membranes tested. The observed difference in flux accompanied by nearly equal cation removal illustrates the great variability of existing RO membranes on the market. These findings also suggest that further advances in membrane technologies will allow for improved performance. Thus, careful attention to both short-term and long-term performance is required for system performance analysis and cost estimation.

Task 6. Preliminary Evaluation of Reclaiming Agricultural Drainage Water for Reuse

Two alternatives have been identified for consideration, both of which provide up to 300,000 acre-feet of reclaimed water from the Alamo River for agricultural irrigation reuse. Both alternatives satisfy the criteria for water reuse, namely sufficient water volumes, adequate water quality for maintaining crop yields, and the availability of commercially available treatment technologies to achieve the desired treatment goals.

- Alternative A involves the reuse of agricultural drainage water with no desalinization treatment.

- Alternative B involves reuse of agricultural drainage water after treatment to remove salinity by RO treatment (and necessary pretreatment processes to ensure effective RO treatment.)

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TABLES AND FIGURES

Table 1. G Values for Jar Test Flocculation Stages

Average G, s^{-1}	First stage G, s^{-1}	Second stage G, s^{-1}	Third stage G, s^{-1}
20	30	20	10
40	55	40	25
60	80	60	40

Table 2. Test Matrix for Jar Testing – Conventional Treatment

Coagulant Scheme	Dose range, mg/L	Average G values, s^{-1}	T, ^oC
Alum	0 - 50	20, 40, 60	12, 20, 30
$FeCl_3$	0 - 50	20, 40, 60	12, 20, 30
Selective calcium softening w/$FeCl_3$	0 - 20	20, 40, 60	12, 20, 30
Excess lime softening w/ $FeCl_3$	0 - 20	20, 40, 60	12, 20, 30

Table 3. Bench-Scale CFS System Design Parameters

Flow rate = 2 L/min (0.5 gal/min)

Rapid -Mix Chamber
    Dimensions: 4" x 4" x 6" (10cm x 10cm x 15cm)
    Volume: 0.42 gal (1.6 L)
    Detention time: 47 sec
    Paddle size: 3" x 5/8" (7.5cm x 1.6cm)
    Rotational speed: 400 rpm
    Velocity gradient, G: 800 s^{-1}
    Gt: 38,000

Flocculation Chambers
    Number = 3 (sequential)
    Dimensions (each): 8.25" x 8.25" x 16" (21cm x 21cm x 41cm)
    Volume: 4.7 gal (17.8L)
    Detention time: 9 min (27 min, total)
    Paddle size: 4.5" x 4" (11.4cm x 10.2cm)
    Velocity gradient, G: (G_{avg} = 40 s^{-1}):
        Chamber 1: G = 55 s^{-1} (29 rpm)
        Chamber 2: G = 40 s^{-1} (24 rpm)
        Chamber 3: G = 25 s^{-1} (18 rpm)

Sedimentation Tank:
    Type: Inclined plate settler
    Tank Dimensions: 8.25" x 30" x 18" (21cm x 76cm x 46cm)
    Volume: 19.3 gal (73.0L)
    Detention time: 37 min
    Overflow rate: 600 gal/ft^2-d (based on inclined plates)
    Inclined plates:
        Angle = 60^o
        Number = 10
        Spacing = 2" (5cm)
        Width = 7.25"

Table 4. MF/UF Cartridge Membrane Specifications

Manufacturer	Koch	Koch
Configuration	HF-1.0-43-PM500	HF-1.0-43-PMF0.1
Membrane material	polysulfone	polysulfone
Module diameter	1 in. (0.0254 m)	1 in. (0.0254 m)
Module length	18 in (0.457 m)	18 in (0.457 m)
Membrane area	1.0 ft^2 (0.09 m^2)	1.0 ft^2 (0.09 m^2)
Fiber count	64-68	64-68
Membrane operating parameters		
Maximum inlet pressure	40 psi (276 kPa)	40 psi (276 kPa)
Maximum TMP	35 psi (241 kPa)	35 psi (241 kPa)
Maximum backflush pressure	20 psi (138 kPa)	20 psi (138 kPa)

Table 5.   Current Annual Inflow to the Salton Sea

Source	Average annual flow, acre-feet/yr
Alamo River	600,000
New River	450,000
Whitewater River	60,000
Direct drainage	190,000
Miscellaneous	30,000
TOTAL INFLOW	1,330,000

Table 6. Alamo River Water Quality Characteristics*

Parameter	Units	Average
pH	pH units	8.0
Temperature	^{o}C	22
Electroconductivity (EC)	dS/m	3.5
Total suspended solids (TSS)	mg/L	560
Total dissolved solids (TDS)	mg/L	2,400
Turbidity	NTU	127
Alkalinity	meq/L	4.5
Hardness	meq/L	17.0
Calcium	mg/L	180
Magnesium	mg/L	97
Sodium	mg/L	460
Potassium	mg/L	11
Barium	mg/L	0.11
Iron	mg/L	0.026
Strontium	mg/L	3.2
Selenium	mg/L	0.007
Chloride	mg/L	540
Sulfate	mg/L	830
Fluoride	mg/L	0.58
Boron	mg/L	0.71
Silica	mg/L	12
TKN	mg/L	2.6
Ammonia nitrogen (as N)	mg/L	1.1
Nitrite + Nitrate nitrogen (as N)	mg/L	7.4
Phosphorus-ortho	mg/L	0.38

*Alexander, R.B., Slack, J.R., Ludtke, A.S., Fitzgerald, K.K. and Schertz, T.L. Data from Selected U.S. Geological Survey National Stream Water-Quality Monitoring Networks (WQN) USGS Digital Data Series DDS-37, Station 10254670 Alamo River at Drop 3 near Calipatria CA.

Table 7. Colorado River Water Quality Characteristics[1]

Parameter	Units	Average
pH	pH units	8.0
Temperature	^oC	21
Electroconductivity (EC)	dS/m	1.2
Total dissolved solids (TDS)	mg/L	840
Turbidity	NTU	4.7
Alkalinity	meq/L	2.9
Hardness	meq/L	7.2
Calcium	mg/L	91
Magnesium	mg/L	32
Sodium	mg/L	140
Potassium	mg/L	5.6
Barium	mg/L	0.11
Iron	mg/L	0.004
Strontium	mg/L	1.2
Selenium	mg/L	0.002
Chloride	mg/L	120
Sulfate	mg/L	340
Fluoride	mg/L	0.48
Boron	mg/L	0.18
Silica	mg/L	7.0
Total nitrogen	mg/L	0.6
Phosphorus-ortho	mg/L	0.01

[1]Alexander, R.B., Slack, J.R., Ludtke, A.S., Fitzgerald, K.K. and Schertz, T.L. Data from Selected U.S. Geological Survey National Stream Water-Quality Monitoring Networks (WQN) USGS Digital Data Series DDS-37, Station 09429490 Colorado River above Imperial Dam, CA-AZ.

Table 8. Salinity Tolerance of Common Imperial Valley Crops*

	Acreage under irrigation	A	B	Tolerance Rating**
Field Crops				
Alfalfa	163,000	2.0	7.3	MS
Wheat	105,000	6.0	7.1	MT
Sudan grass	84,000	2.8	4.3	MT
Bermuda grass	46,000	6.9	6.4	T
Sugar beets	17,000	5.6	7.6	T
Cotton	4,000	7.7	5.2	T
Rye grass	3,000	5.6	7.6	MT
Sorghum	3,000	6.8	16.0	MT
Partial Sum	425,000			
Garden Crops				
Carrots	17,000	1.0	14.0	S
Onions	16,000	1.2	16.0	S
Cantaloupes	13,000			
Lettuce	9,400	1.3	13.0	MS
Broccoli	6,000	2.8	9.2	MS
Corn, ear	4,500	1.7	12.0	MS
Cauliflower	3,000			MS
Watermelon	3,000			MS
Potatoes	2,500	1.7	12.0	MS
Tomatoes	2,000	2.5	9.9	MS
Partial Sum	76,400			
Permanent Crops				
Duck ponds	8,800			
Asparagus	5,300	4.1	2.0	T
Grapefruit	1,200	1.8	16.0	S
Lemons	1,150			S
Fish farms	1,150			
Partial Sum	17,600			
Total acreage under irrigation in Imperial Valley	560,000			

*Jensen, M.E. and Walter, I.A. "Assessment of 1987-1996 Water Use by the Imperial Irrigation District using Water Balance and Cropping Data," U.S. Bureau of Reclamation, Boulder City, NV, June 1997.

Table 9. Relative Crop Yield as a Function of Average Root Zone Salinity

	Relative Yield (Y), Percent								
	EC_s, dS/m								
Field Crops	1.9	2.0	2.2	2.5	3.0	3.5	4.0	4.5	5.0
Alfalfa	100	100	99	96	93	89	85	82	78
Wheat	100	100	100	100	100	100	100	100	100
Sudan grass	100	100	100	100	99	97	95	93	91
Bermuda grass	100	100	100	100	100	100	100	100	100
Sugar beets	100	100	100	100	100	100	100	100	100
Cotton	100	100	100	100	100	100	100	100	100
Rye grass	100	100	100	100	100	100	100	100	100
Sorghum	100	100	100	100	100	100	100	100	100
Garden Crops									
Carrots	87	86	83	79	72	65	58	51	44
Onions	89	87	84	79	71	63	55	47	39
Cantaloupes	100	100	100	100	100	100	100	100	100
Lettuce	92	91	88	84	78	71	65	58	52
Broccoli	100	100	100	100	98	94	89	84	80
Corn, ear	98	96	94	90	84	78	72	66	60
Cauliflower	100	100	100	100	100	100	100	100	100
Watermelon	100	100	100	100	100	100	100	100	100
Potatoes	98	96	94	90	84	78	72	66	60
Tomatoes	100	100	100	100	95	90	85	80	75
Permanent Crops									
Duck ponds	NA	NA	NA	NA	NA	NA	NA	NA	NA
Asparagus	100	100	100	100	100	100	100	99	98
Grapefruit	98	97	NA	89	81	73	65	57	49
Lemons	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fish farms	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 10. Relative Susceptibility of Crops to Leaf Damage by Sodium or Chloride through Spray Irrigation

<5 meq/L	5 - 10 meq/L	10 - 20 meq/L	>20 meq/L
Citrus	Potato Tomato	Alfalfa Corn Sorghum	Cauliflower Sorghum Sugar beet

Table 11. Relative Susceptibility of Crops to Boron Toxicity

Very sensitive, <0.5 mg/L	Sensitive, 0.5 – 0.75 mg/L	Sensitive, 0.75 – 1 mg/L	Moderately sensitive, 1 – 2 mg/L	Moderately tolerant, 2 – 4 mg/L	Tolerant, 4 – 6 mg/L	Very tolerant, 6 – 15 mg/L
Lemons	Grapefruit	Wheat	Carrots Potatoes	Cauliflower Corn Lettuce Onions	Alfalfa Sugar beets Tomatoes	Asparagus Cotton Sorghum

Table 12. Water Quality Guidelines for SAR

SAR	EC_w of the irrigation water, dS/m		
	No restrictions	Slight to moderate	Severe
0 –3	>0.7	0.7 – 0.2	<0.2
3 – 6	>1.2	1.2 – 0.3	<0.3
6 – 12	>1.9	1.9 – 0.5	<0.5
12 – 20	>2.9	2.9 – 1.3	<1.3
20 – 40	>5.0	5.0 – 2.9	<2.9

Table 13. Suggested Water Quality Criteria Guidelines for Irrigation

Parameter	Units	Limit	Restriction
Salinity	dS/m	2.5	Higher salinity may result in greater than 10% reduction in relative crop yield
Sodium	meq/L	20 (5)	Sodium toxicity (Leaf damage through spray irrigation)
Chloride	meq/L	5	Potential leaf damage
Boron	mg/L	0.5	Based on potential toxicity to lemon trees
SAR		12	Prevention of soil permeability physical soil property changes; based on the salinity limit of 2.5 dS/m

Table 14. Comparisons of Colorado River and Alamo River Waters with Suggested Water Quality Criteria Guidelines for Irrigation

Parameter	Units	Limit	Colorado River	Alamo River
Salinity	dS/m	2.5	1.2	3.5
Sodium	meq/L	20 (5)	6.1	20
Chloride	meq/L	5	3.4	15.2
SAR		12	3.2	6.9

Table 15.. Average Raw and Plain Settled Alamo River Water Quality

Parameter	Raw, mg/L	1-hr settled, mg/L	% Reduction	24-hr settled, mg/L	% Reduction
TSS	258	110	57	37	86
Turbidity	80	50	38	26	68
No. of readings	18	15	-	6	-

Table 16. CFS Treatment Performance – Alum Coagulation

Parameter	Units	No. of runs	Raw		CFS		Percent reduced
			Average	Range	Average	Range	
pH	pH units	5	8.0	7.8-8.1	7.7	7.6-7.8	-
EC	dS/m	5	3.47	3.08-3.88	3.36	3.01-3.76	-
TSS	mg/L	5	255	126-470	10.7	8.1-15.6	95.8
Turbidity	NTU	5	79	55-105	3.3	2.8-4.1	95.8

Table 17. DMF Treatment Performance – Alum Coagulation

Parameter	Units	Raw	CFS	DMF		
				2 gpm/ft^2	4 gpm/ft^2	6 gpm/ft^2
TSS	mg/L	255	10.7	1.6	1.3	2.1
Turbidity	NTU	79	3.3	0.39	0.40	0.57
SDI		NA	>5	3.4		

Table 18. DMF Treatment Performance – Headloss Buildup Rate

Coagulant	Headloss rate, in/hr		
	2 gpm/ft^2	4 gpm/ft^2	6 gpm/ft^2
Alum	0.27	0.85	1.33
Ferric chloride	0.27	0.64	1.39

Table 19. CFS Treatment Performance – Ferric Chloride Coagulation

Parameter	Units	No. of runs	Raw		CFS		Percent reduced
			Average	Range	Average	Range	
pH	pH units	5	8.1	7.8-8.3	7.7	7.7-7.8	-
EC	dS/m	5	3.44	3.21-3.70	3.49	3.25-3.71	-
TSS	mg/L	5	244	218-278	7.8	5.0-11.7	96.8
Turbidity	NTU	5	81	75-84	2.3	1.9-2.6	97.2

Table 20. DMF Treatment Performance – Ferric Chloride Coagulation

Parameter	Units	Raw	CFS	DMF		
				2 gpm/ft^2	4 gpm/ft^2	6 gpm/ft^2
TSS	mg/L	244	7.8	2.0	1.6	1.8
Turbidity	NTU	81	2.3	0.43	0.43	0.49
SDI		NA	>5	3.1		

Table 21. Estimated Lime and Soda Ash Requirements
for Selective Calcium Softening

Lime requirement		Soda ash requirment	
mg/L	lb/MG	mg/L	lb/MG
173	1,440	239	1,990

Table 22. CFS Treatment Performance – Selective Calcium Softening

Parameter	Units	No. of runs	Raw		CFS		Percent reduced
			Average	Range	Average	Range	
PH	pH units	4	8.1	8.0-8.1	9.9	9.3-10.1	-
EC	dS/m	4	3.30	2.75-3.66	3.19	2.69-3.56	-
TSS	mg/L	4	275	195-348	8.6	4.5-14.9	96.9
Turbidity	NTU	4	80	70-89	2.8	1.2-5.3	96.5

Table 23. DMF Treatment Performance – Selective Calcium Treatment

Parameter	Units	Raw	CFS	DMF		
				2 gpm/ft^2	4 gpm/ft^2	6 gpm/ft^2
pH	pH units	8.1	9.7	8.0	7.9	7.9
TSS	mg/L	275	14.9	1.0	1.1	1.6
Turbidity	NTU	80	4.3	0.34	0.29	0.40
Total hardness	meq/L	16.9	NA	11.0		
Ca hardness	meq/L	9.0	NA	3.9		
SDI		NA	>5	3.3		

Table 24. Headloss Buildup Rate – Selective Calcium Softening Treatment

Headloss rate, in/hr		
2 gpm/ft^2	4 gpm/ft^2	6 gpm/ft^2
0.082	0.17	0.37

Table 25. Summary of Flat-Sheet MF/UF Membrane Characteristics

Manufacturer	Type	Material	Manufacturer [MWCO]	Manufacturer CWF [(m^3/m^2-d-kPa)]	Measured CWF [(m^3/m^2-d-kPa)]	Rm
Millipore	ZM500	Nonionic, hydrophilic polysulfone	500,000	0.836-1.254	0.885	1.3
Millipore	YM10	Nonionic, regenerated cellulose	10,000	0.021-0.042	0.008	476

Table 26. Average Raw, Settled Raw, and
Stirred-Cell MF/UF Filtration Effluent Parameters

Parameter	Raw Water	Settled Raw	YM10	ZM500
TSS, mg/L	270	96	<1	<1
Turbidity, NTU	80	48	0.4	0.1

Table 27. Average, Minimum and Maximum Influent and
Effluent Water Quality for CFMF Experiments

Parameter	Unit	Raw Alamo River Water		Settled Raw Alamo River Water	
		CFMF Influent (N=5)	CFMF Effluent (N=5)	CFMF Influent (N=6)	CFMF Effluent (N=6)
Turbidity	NTU	81 (70-89)	0.19 (0.12-0.28)	14.4 (7.8-19.0)	0.24 (0.12-0.51)
TSS	mg/L	270 (195-348)	<1	29.3 (21.6-37.5)	<1
SDI	%	1)	3.63 (2.4-4.6)	1)	1.81 (0.0-4.3)

1) not measured

Table 28 Average Effluent Water Quality for Conventional Treatment -
Dual Media Filtration (DMF) and Microfiltration (CFMF) Treatment

Parameter	Unit	DMF[a] (N=6)	CFMF[b]-raw (N=7)	CFMF[b]-settled raw (N=6)
Turbidity	NTU	0.45	0.20	0.23
Total suspended solids	mg/L	1.9	0.6	1.5
Silt density index		3.3	3.3	2.3

[a]Conventional includes both alum and ferric chloride coagulation, not softening
[b]CFMF combined results – PM500 and PMF0.1

Table 29. Cation Removal by RO Treatment: ESPA and LFCI Flat-Sheet Membranes

Cations	Influent, mg/L	ESPA		LFCI	
		Effluent, mg/L	% removed	Effluent, mg/L	% removed
Aluminum	0.22	0.021	90.5	0.013	94.1
Barium	0.046	0.005	89.1	0.0011	97.6
Calcium	179	2.2	98.8	1.5	99.2
Copper	0.014	0.015	0.0	0.017	0.0
Iron	0.085	0.011	87.1	0.0073	91.4
Potassium	16.2	0.64	96.0	0.41	97.5
Magnesium	96	0.41	99.6	0.26	99.7
Manganese	0.0025	0.006	0.0	0.0044	0.0
Sodium	417	25.8	93.8	21.4	94.9
Strontium	2.47	0.016	99.4	0.015	99.4
Silica	4.37	0.213	95.1	0.127	97.1

Table 30. Estimated Water Quality of Blended Alamo River-Colorado River Irrigation Water

Parameter	Units	Limit	Volume of Alamo River Reclaimed, mafy			
			0	0.1	0.2	0.3
Salinity	dS/m	2.5	1.2	1.3	1.4	1.6
Sodium	meq/L	20 (5)	6.1	6.6	7.3	8.2
Chloride	meq/L	5	3.4	3.8	4.4	5.2
SAR		12	3.2	3.4	3.6	3.9

Table 31. Dose Range or Doses for Jar Tests

Coagulant/Softening Scheme	Dose or dose range, mg/L			
	Alum	$FeCl_3$	Lime	Soda ash
Alum	0 – 100	0	0	0
Ferric chloride	0	0 - 50	0	0
Selected calcium	0	0 - 50	175	240

Table 32. G Values for Jar Test Flocculation Stages

Average G, s^{-1}	1st stage G, s^{-1}	2nd stage G, s^{-1}	3rd stage G, s^{-1}
20	30	20	10
40	55	40	25
60	80	60	40

Table 33. Bench-Scale CFS System Design Parameters

Flow rate = 2 L/min (0.5 gal/min)
Rapid -Mix Chamber Dimensions: 4" x 4" x 6" (10cm x 10cm x 15cm) Volume: 0.42 gal (1.6 L) Detention time: 47 sec Paddle size: 3" x 5/8" (7.5cm x 1.6cm) Rotational speed: 400 rpm Velocity gradient, G: 800 s^{-1} Gt: 38,000
Flocculation Chambers Number = 3 (sequential) Dimensions (each): 8.25" x 8.25" x 16" (21cm x 21cm x 41cm) Volume: 4.7 gal (17.8L) Detention time: 9 min (27 min, total) Paddle size: 4.5" x 4" (11.4cm x 10.2cm) Velocity gradient, G: (G_{avg} = 40 s^{-1}): Chamber 1: G = 55 s^{-1} (29 rpm) Chamber 2: G = 40 s^{-1} (24 rpm) Chamber 3: G = 25 s^{-1} (18 rpm)
Sedimentation Tank: Type: Inclined plate settler Tank Dimensions: 8.25" x 30" x 18" (21cm x 76cm x 46cm) Volume: 19.3 gal (73.0L) Detention time: 37 min Overflow rate: 600 gal/ft^2-d (based on inclined plates) Inclined plates: Angle = 60^o Number = 10 Spacing = 2" (5cm) Width = 7.25"

Table 34. Bench-Scale DMF Design Parameters

Flow rates = 10L/hr, 20L/hr, 30 L/hr
Bed Media: Anthracite: 24" (61 cm), effective size = 1.5 mm Sand: 8" (20 cm), effective size = 0.55 mm Filtration rates: 2, 4, and 6 gpm/ft^2 (4.9, 9.8, and 14.5 m^3/m^2-hr) Maximum Headloss: 6.5 ft (200 cm)

Table 35. G Values and Paddle Speeds for CFS Flocculation Stages

Average G, s^{-1}	1st stage G, s^{-1}	2nd stage G, s^{-1}	3rd stage G, s^{-1}
40	55 (29 rpm)	40 (24 rpm)	25 (18 rpm)
60	80 (39 rpm)	60 (32 rpm)	40 (24 rpm)

Table 36. Stirred Cell Design Specifications

Stirred-Cell Cell: Amicon, model 8200 [Millipore Corporation] Membrane size: 63.5 mm Pressure: 0-75 psi N_2 Feed tanks: Acrylic glass, 10L and 5L.

Table 37. CFMF Design Specifications

CFMF
Piping: PVC Schedule 40, 1” Dia.
Tubing: High Pressure Reinforced, 1” Dia.
Couplings: Banjo Corporation
Pump: Grundfos, 3 hp, type CR4-60-U.
Valves: Gate Valves, Brass 1”.
Flowmeter: Burkert Model 8035 [Cole Parmer]

Table 38. RO Flat-Sheet Test Cell Design Specifications

RO
Test cell: Custom manufactured
Membrane size:1” X 2.5”
Motor: Carbonator pump $^{1}/_{3}$ hp; Dayton model 2R958
Pump: Procon 103A070F31
Fittings/Tubing: Swagelok, ½, $^{3}/_{8}$, ¼ “ Dia. Stainless steel
Flowmeter: Cole Parmer

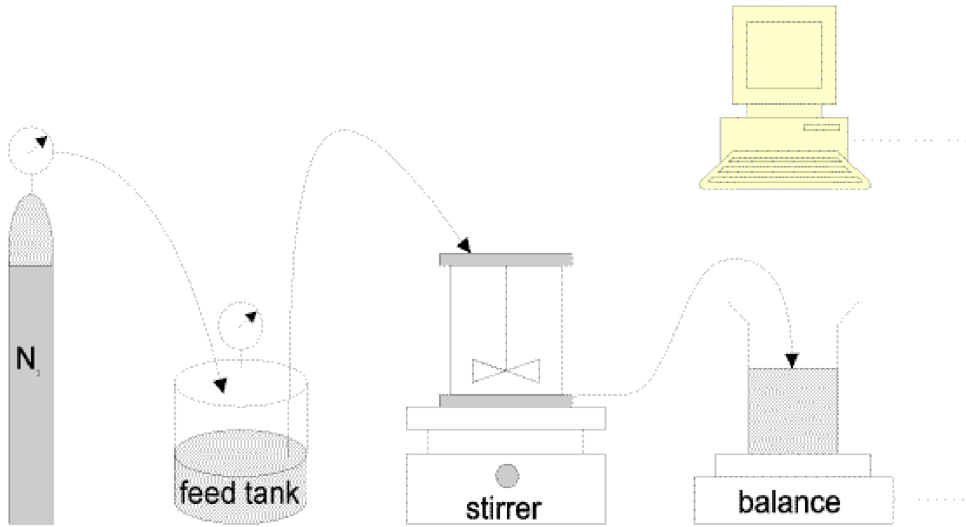

Figure 1. Schematic of Stirred-Cell Membrane Testing Apparatus

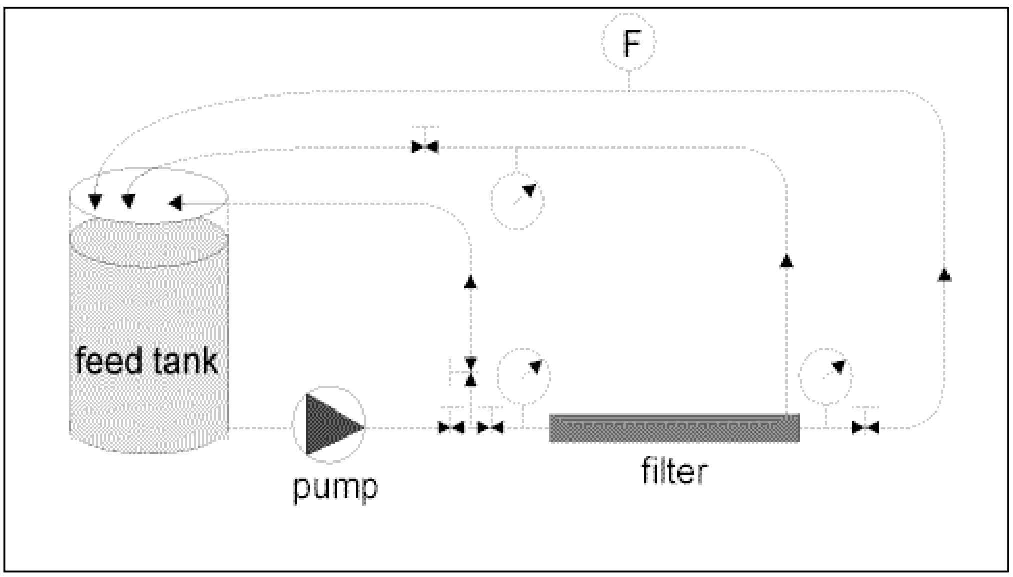

Figure 2. Schematic of Continuous-Flow Membrane Filtration (CFMF) Apparatus

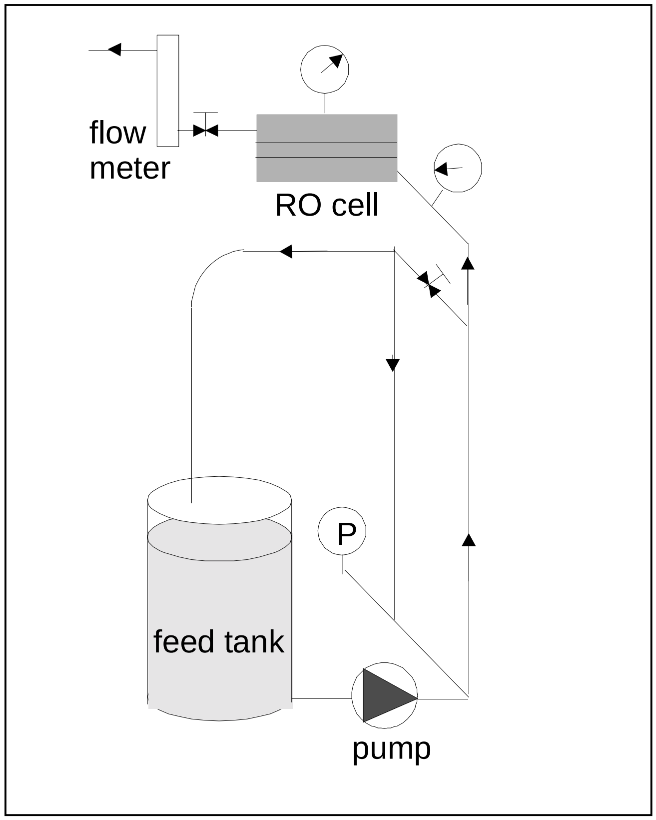

Figure 3. Schematic of Continuous-Flow RO Flat-Sheet Test Cell

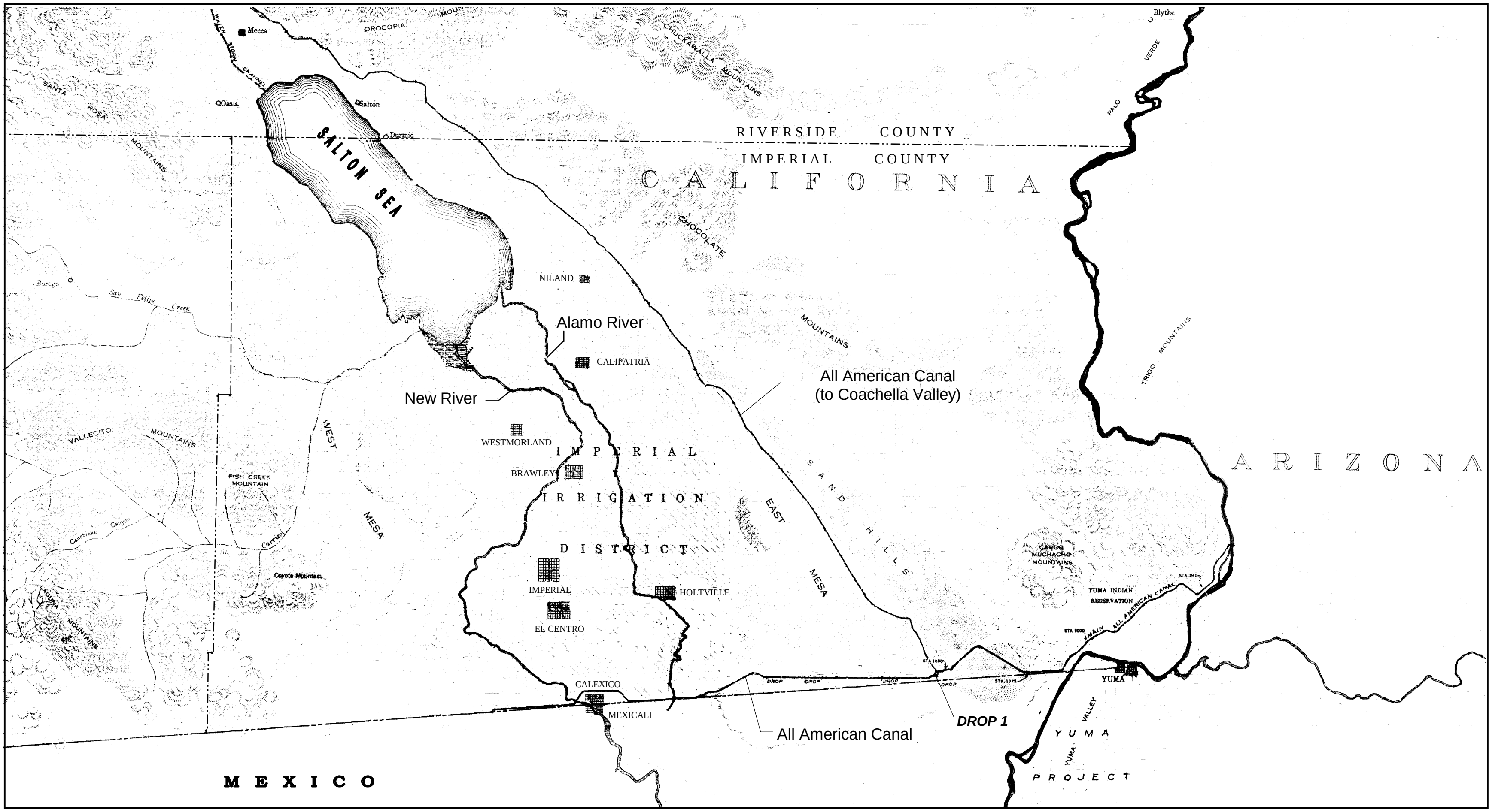

Figure 4. Location of Alamo River, New River, and the Salton Sea

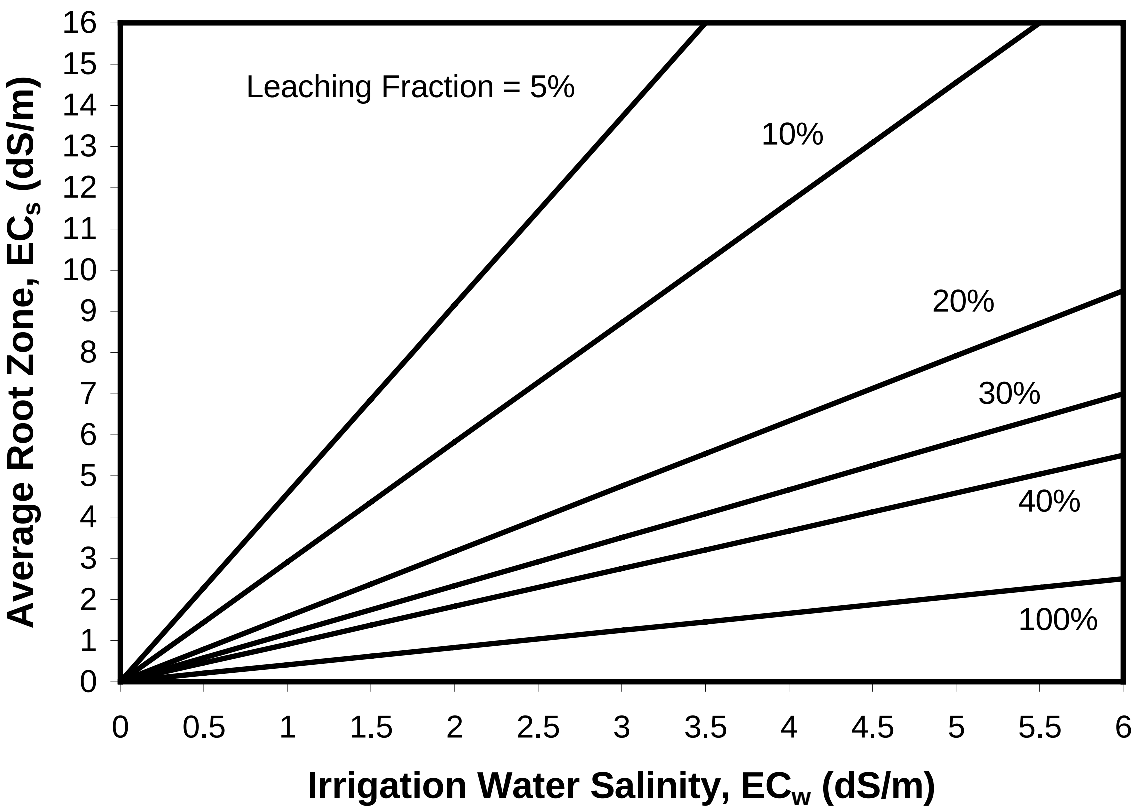

Figure 5. Average Root Zone Salinity Based on Irrigation Water Salinity and Leaching Fraction

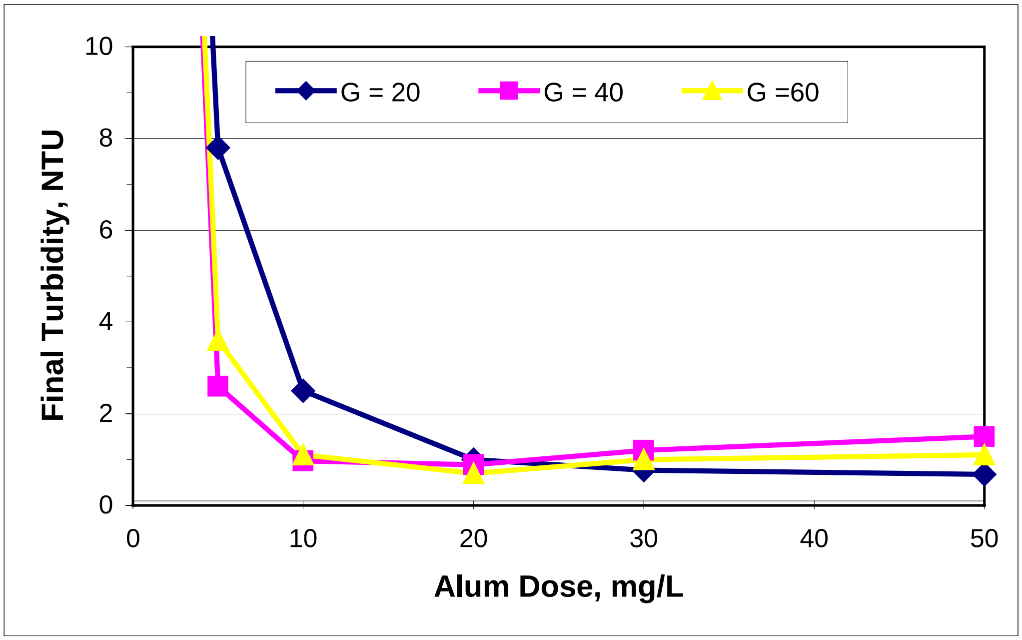

Figure 6. Alum Jar Test Results - Dosage and G Value

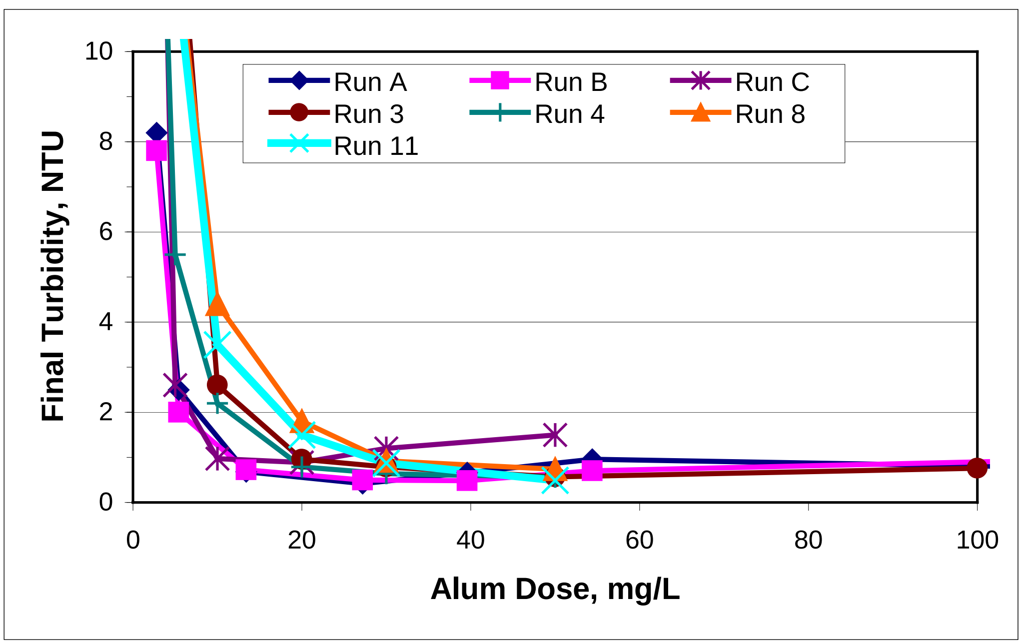

Figure 7. Alum Jar Test Results for Continuous-Flow System Pre-Tests

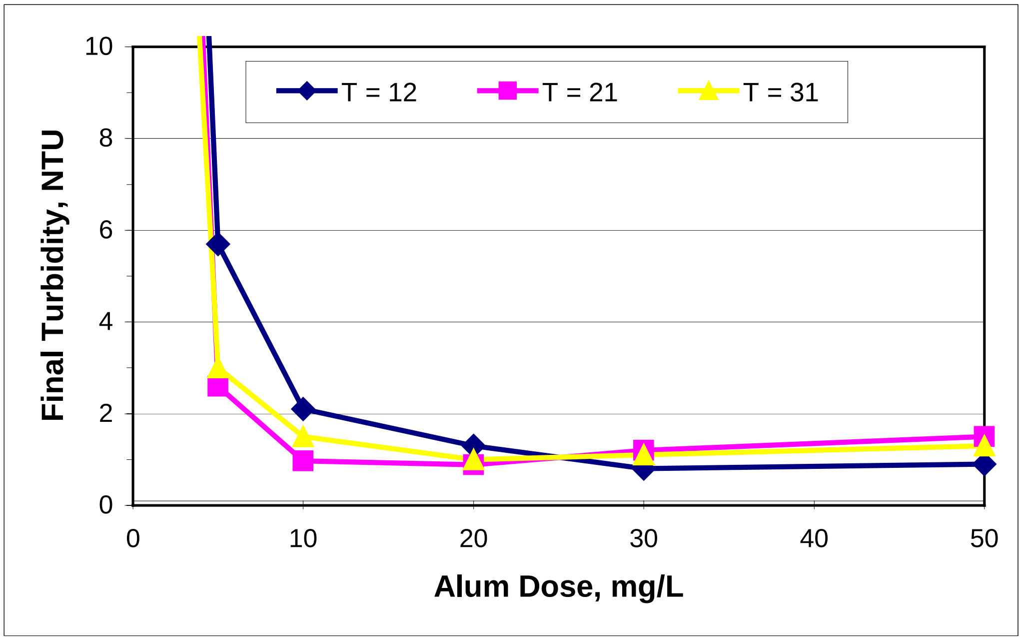

Figure 8. Alum Jar Test Results - Temperature Effects

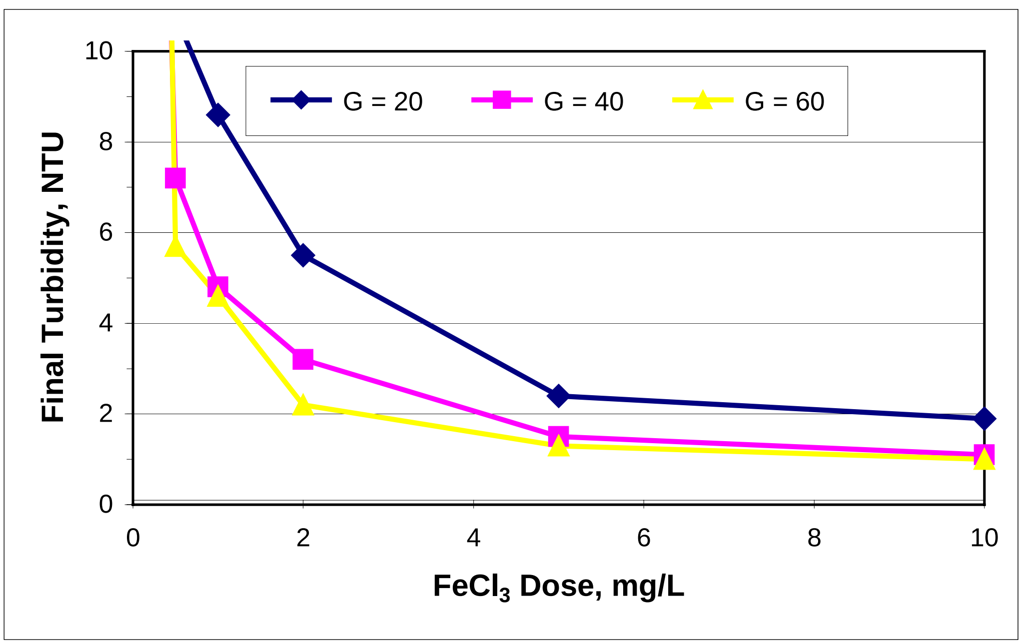

Figure 9. Ferric Chloride Jar Test Results (Set A) - Dosage and G Value

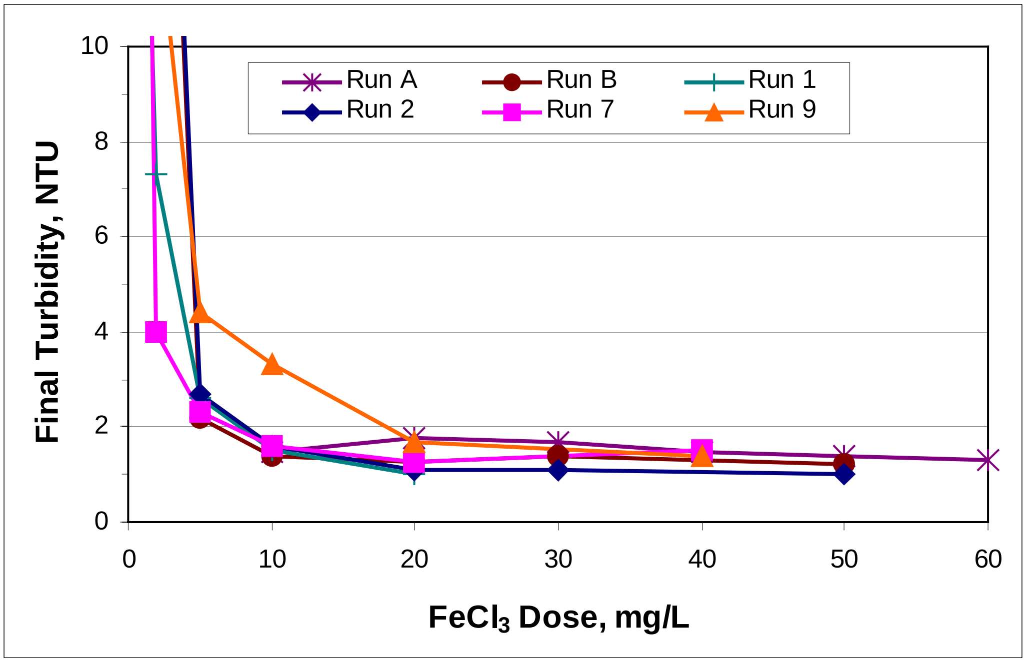

Figure 10. Ferric Chloride Jar Test Results for Continuous-Flow System Pre-Tests

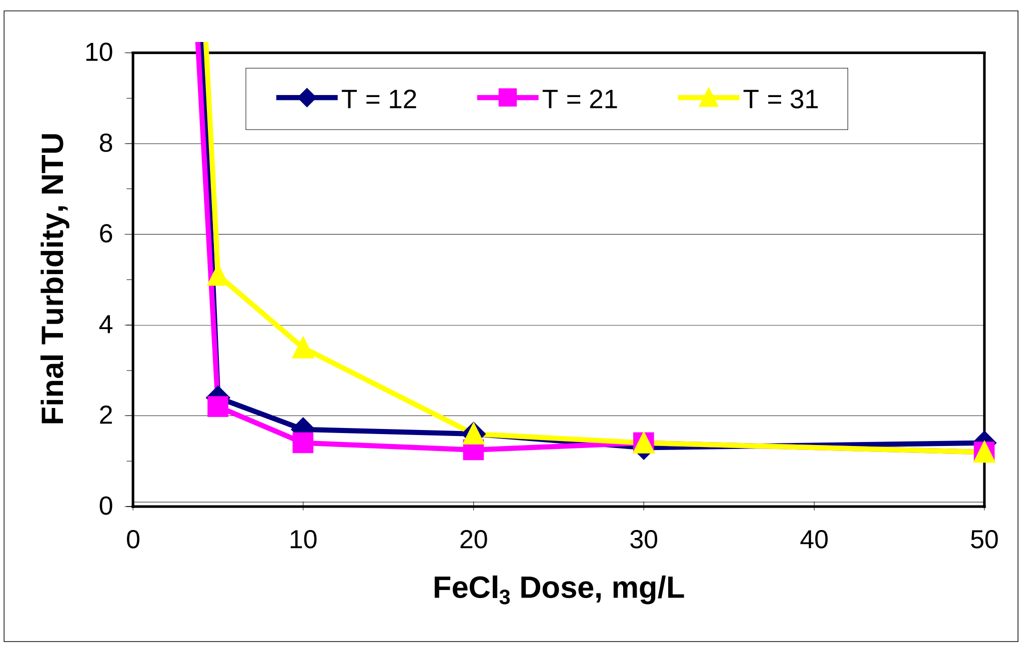

Figure 11. Ferric Chloride Jar Test Results - Temperature Effects

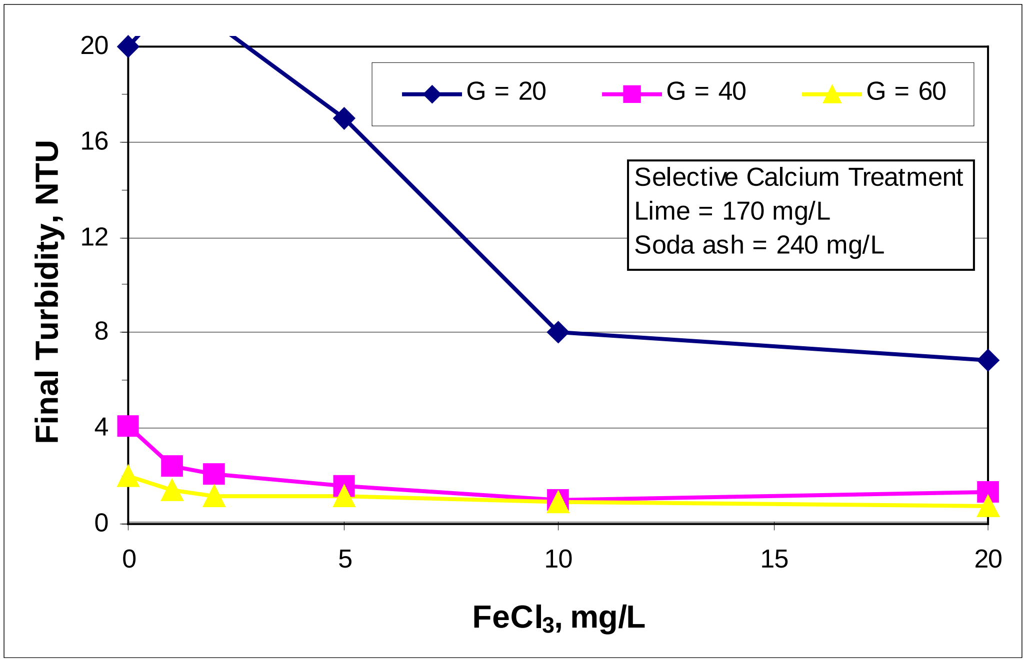

Figure 12. Selective Calcium Jar Test Results - Dosage and G Value

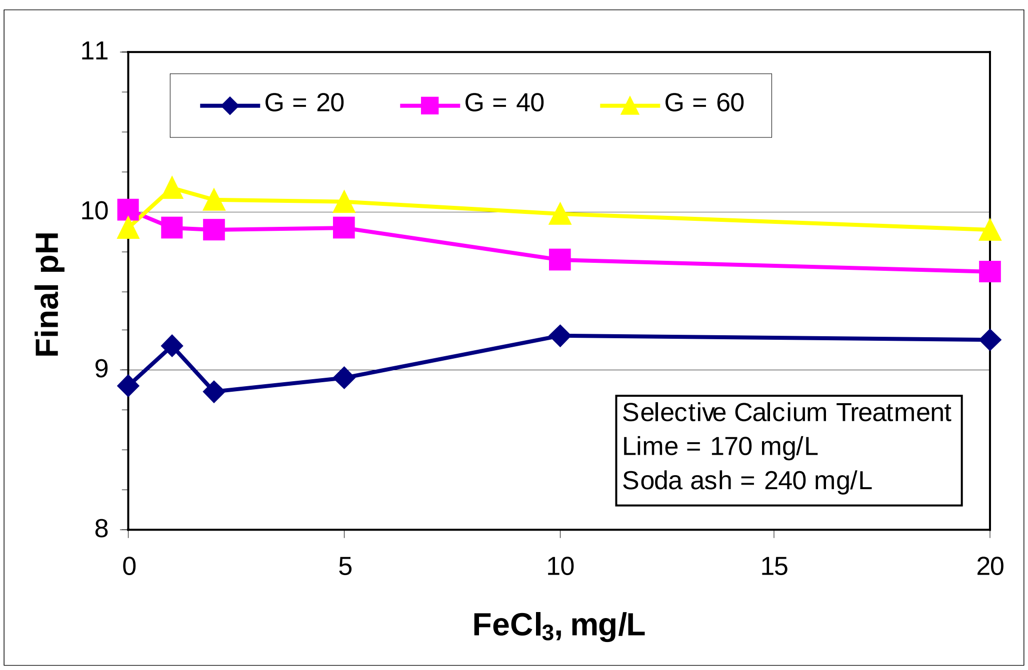

Figure 13. Effect of G Value on Final pH

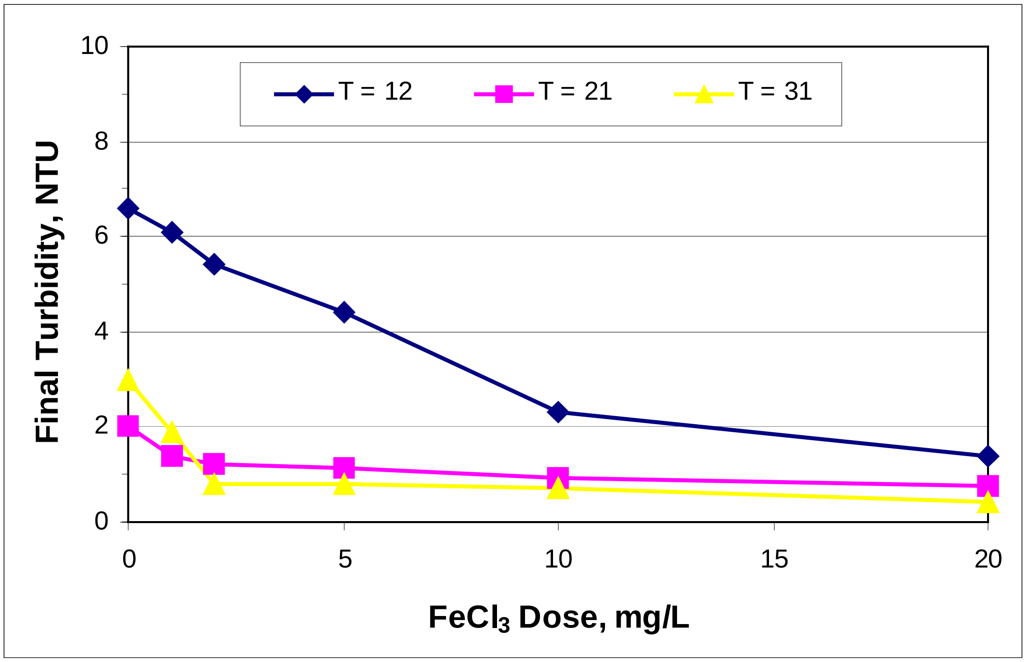

Figure 14. Selective Calcium Jar Test Results – Temperature Effects

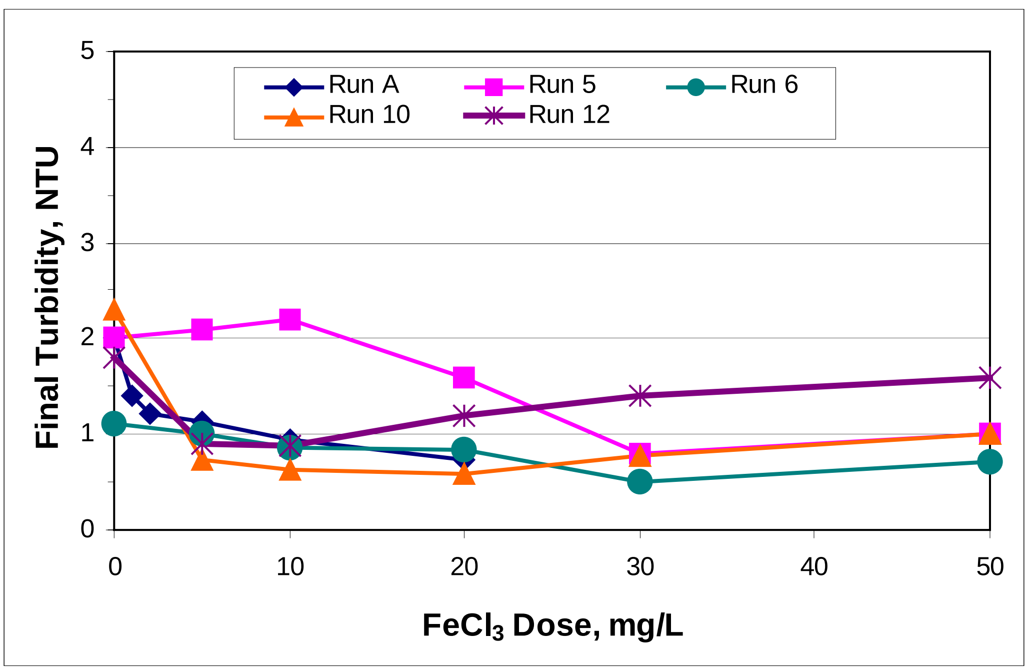

Figure 15. Softening Jar Test Results for Continuous-Flow System Pre-Tests

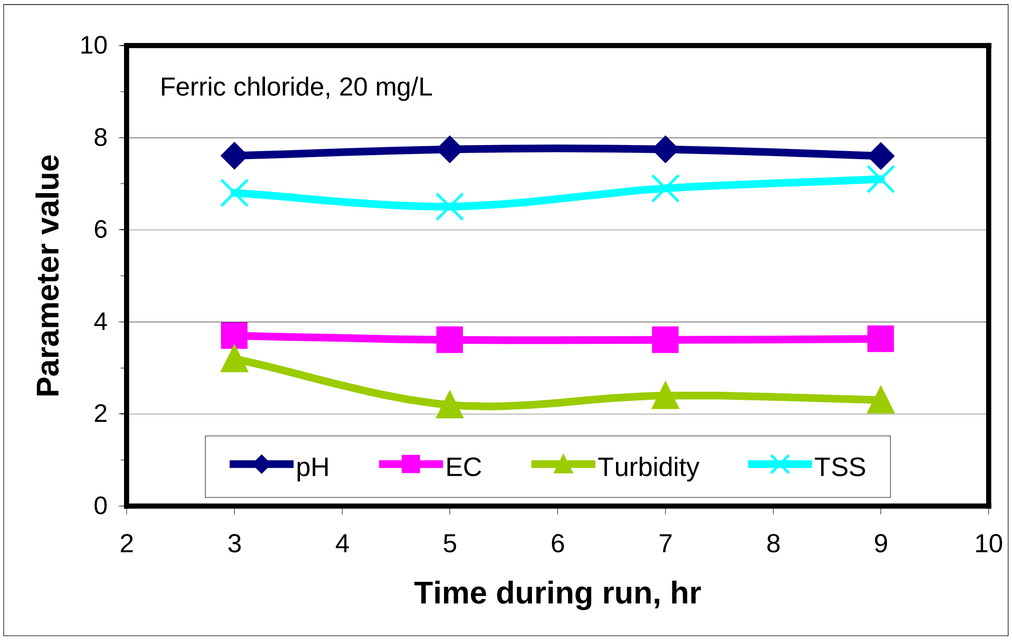

Figure 16. CFS Grab Sample Results – Ferric Chloride Run 1

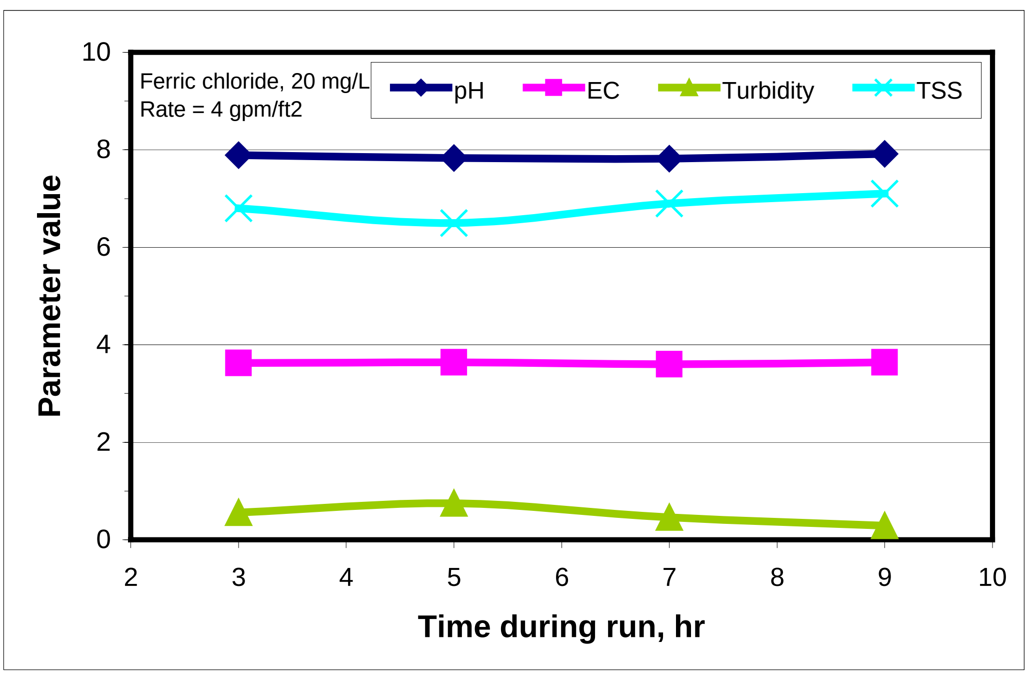

Figure 17. DMF Grab Sample Results – Ferric Chloride Run 1

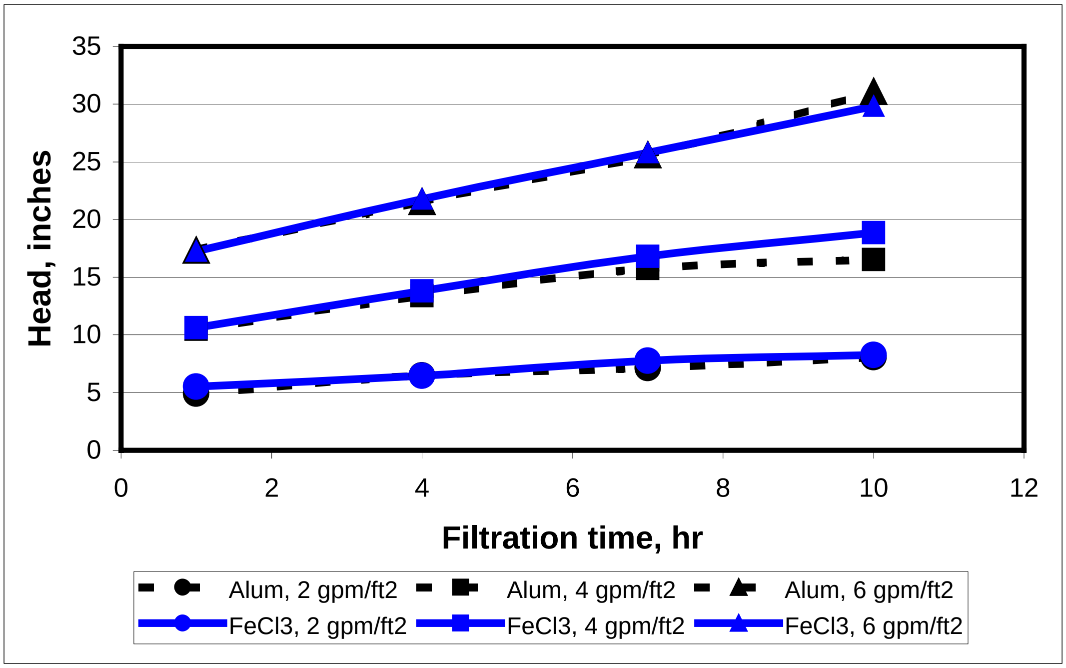

Figure 18. DMF Headloss Rate Curves

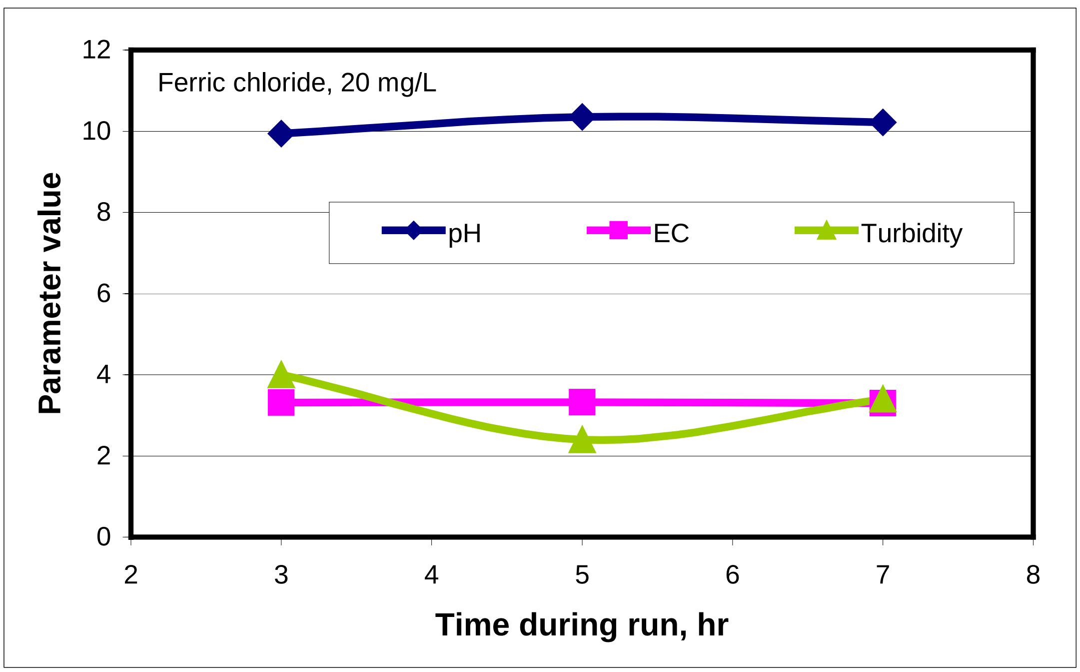

Figure 19. CFS Grab Sample Results – Softening Run 5

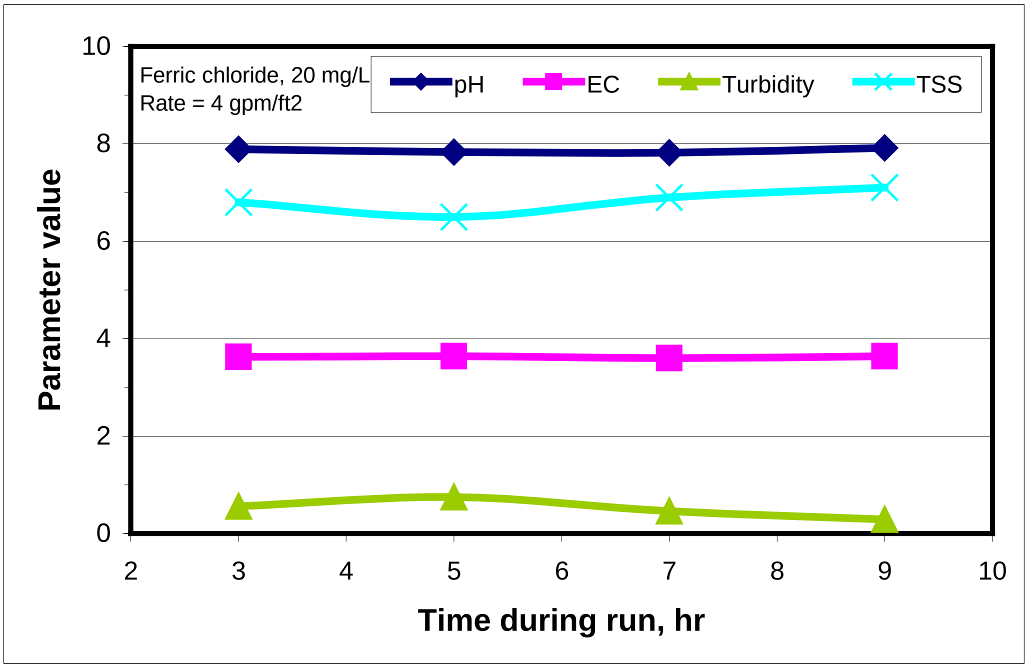

Figure 20. DMF Grab Sample Results – Selective Calcium Softening Run 5

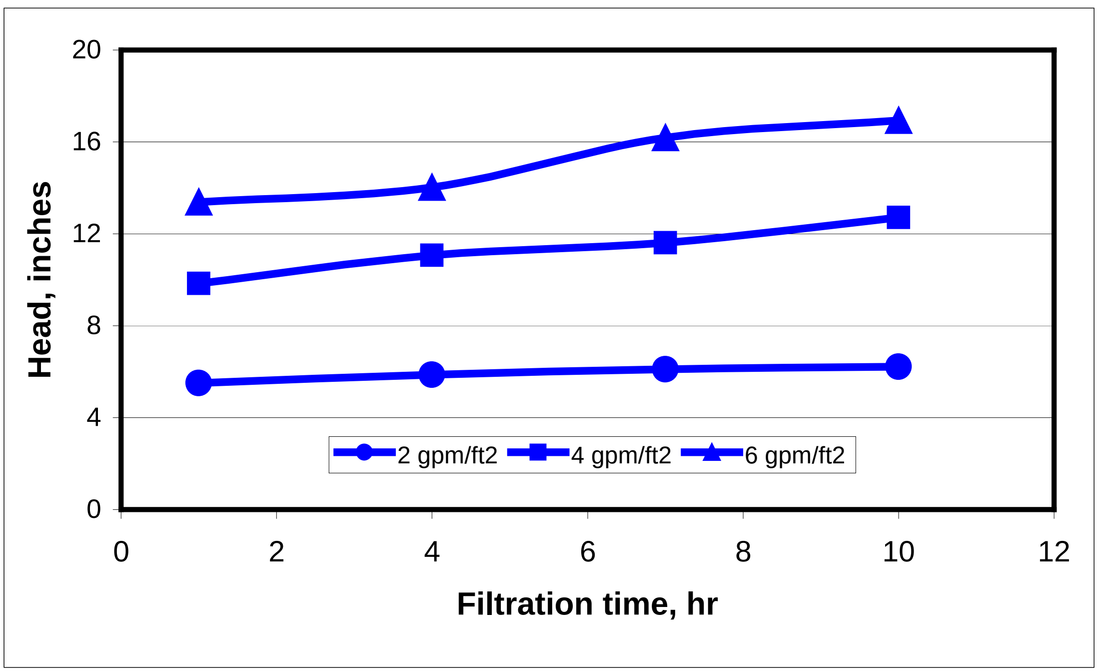

Figure 21. DMF Headloss Rate Curves – Selective Calcium Softening Treatment

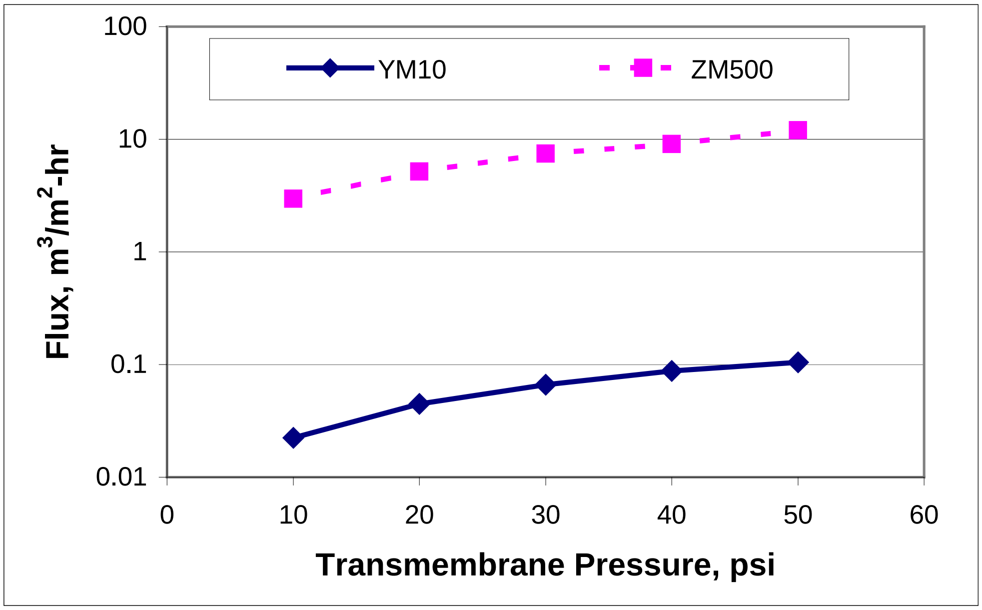

Figure 22. Clean Water Flux for YM10 and ZM500 MF/UF Filter Membranes

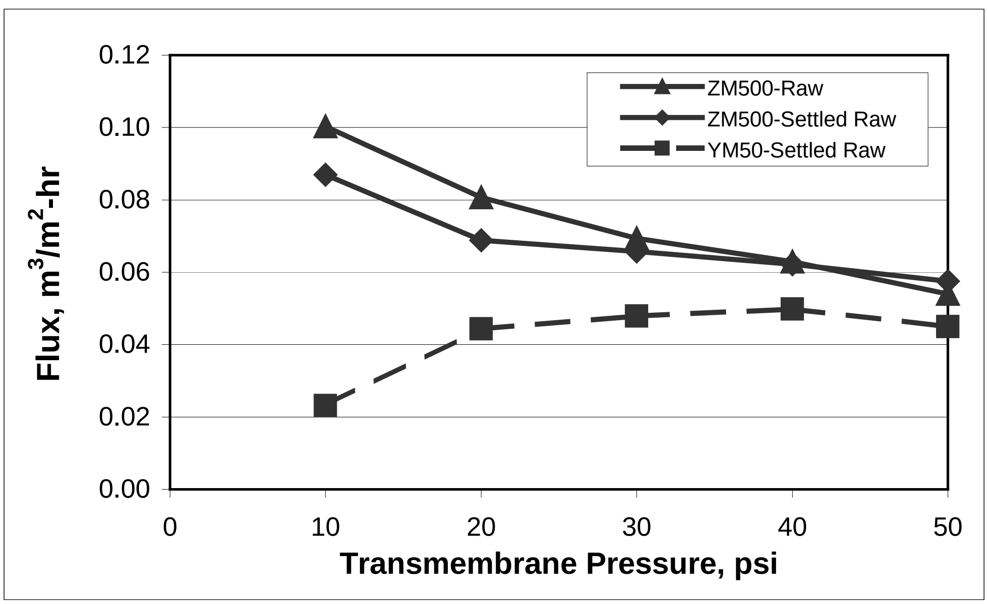

Figure 23. Permeate Flux-TMP Relationship for Alamo River Water Influent

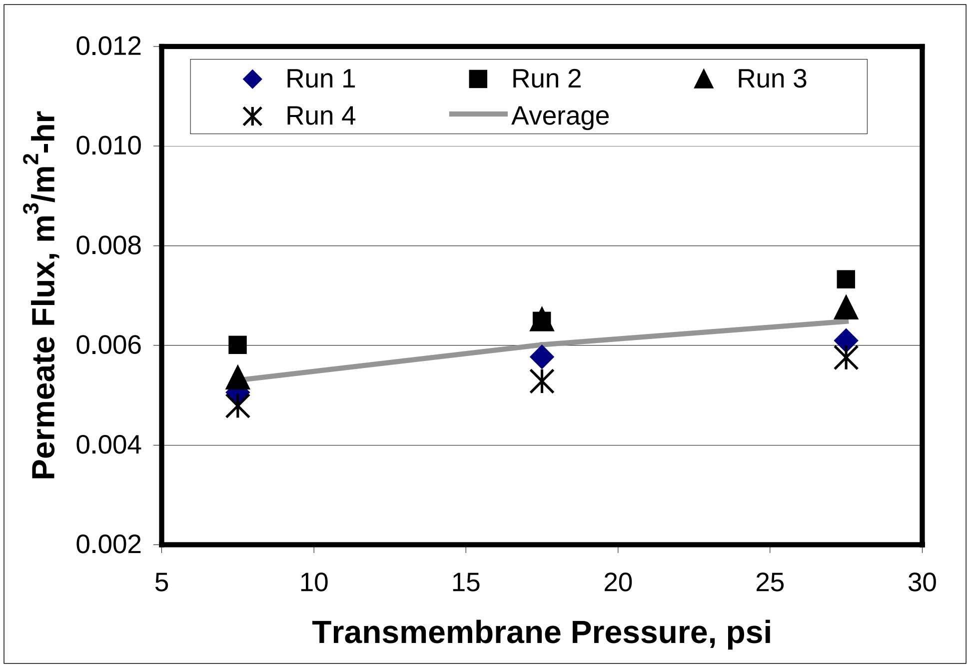

Figure 24. Permeate Flux vs TMP for Settled-Raw Alamo River Water – PM500 Membrane

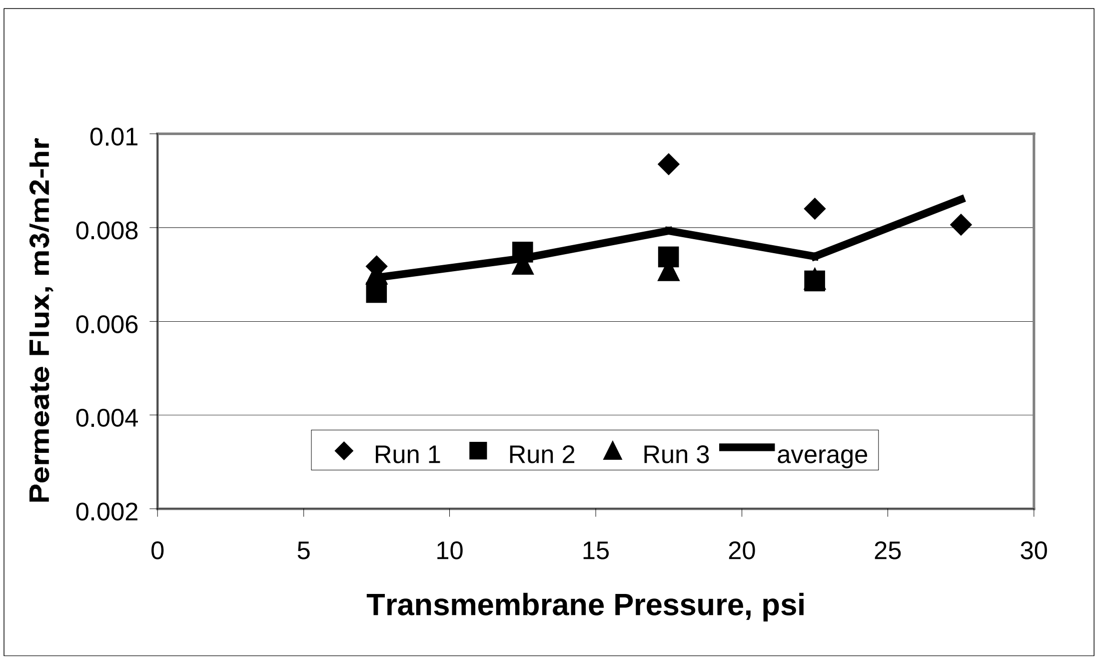

Figure 25. Permeate Flux vs TMP for Settled-Raw Alamo River Water – PMF0.1 Membrane

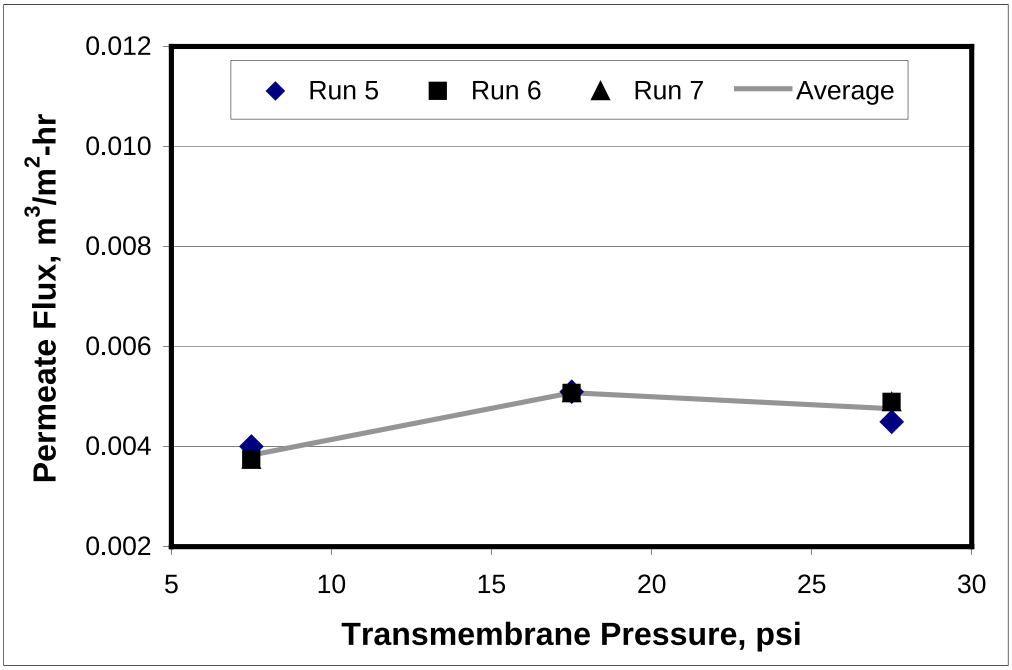

Figure 26. Permeate Flux versus TMP Pressure for Raw Alamo River Water – PM500

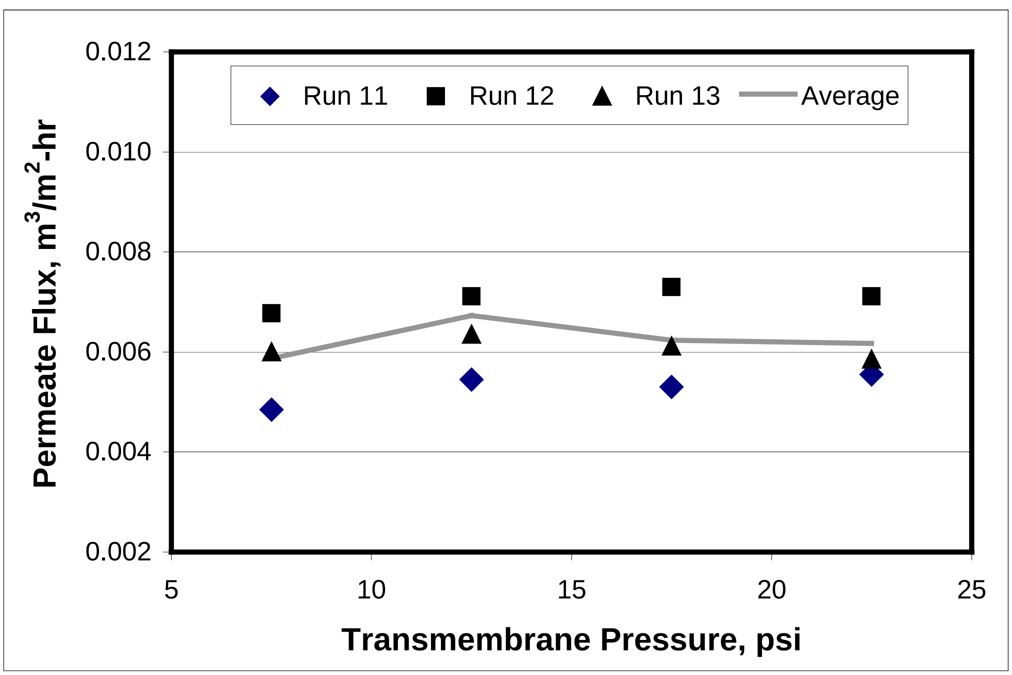

Figure 27. Permeate Flux versus TMP Pressure for Raw Alamo River Water – PMF0.1

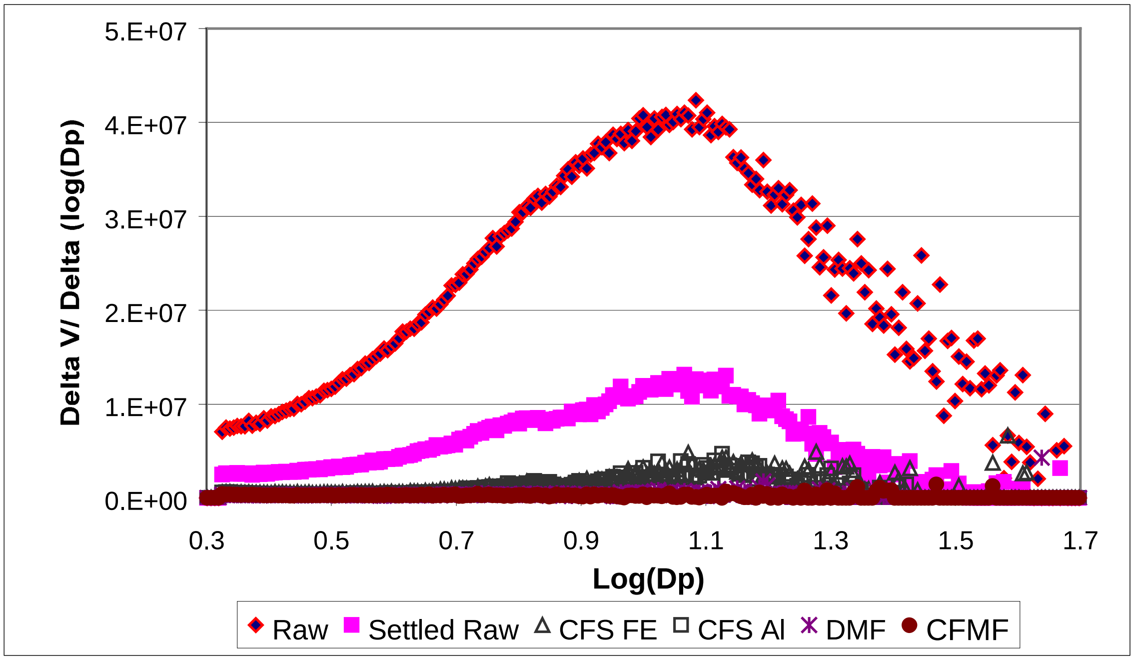

Figure 28. Particle Size Distribution for Alamo River Water – Raw, Settled Raw, After Conventional Treatment with Ferric Chloride (FE) & Alum (Al), After Dual Media Filtration (DMF), and After Microfiltration (CFMF)

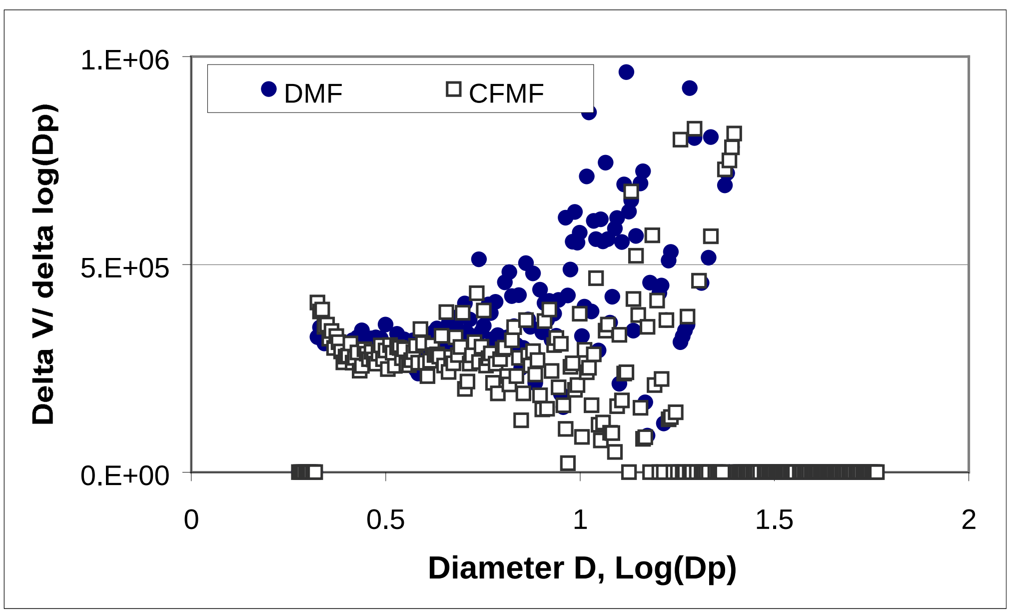

Figure 29. Particle Size Distribution for Alamo River Water After Conventional Treatment with Dual Media Filtration (DMF) and after Microfiltration (CFMF)

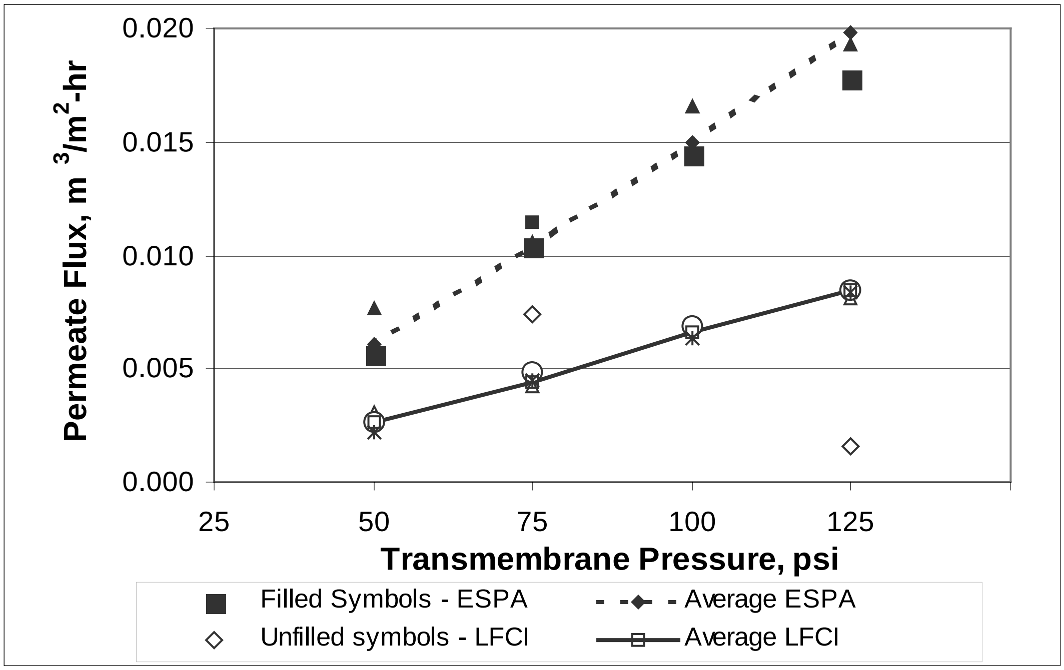

Figure 30. Permeate Flux versus TMP for CFMF Treated Alamo River Water

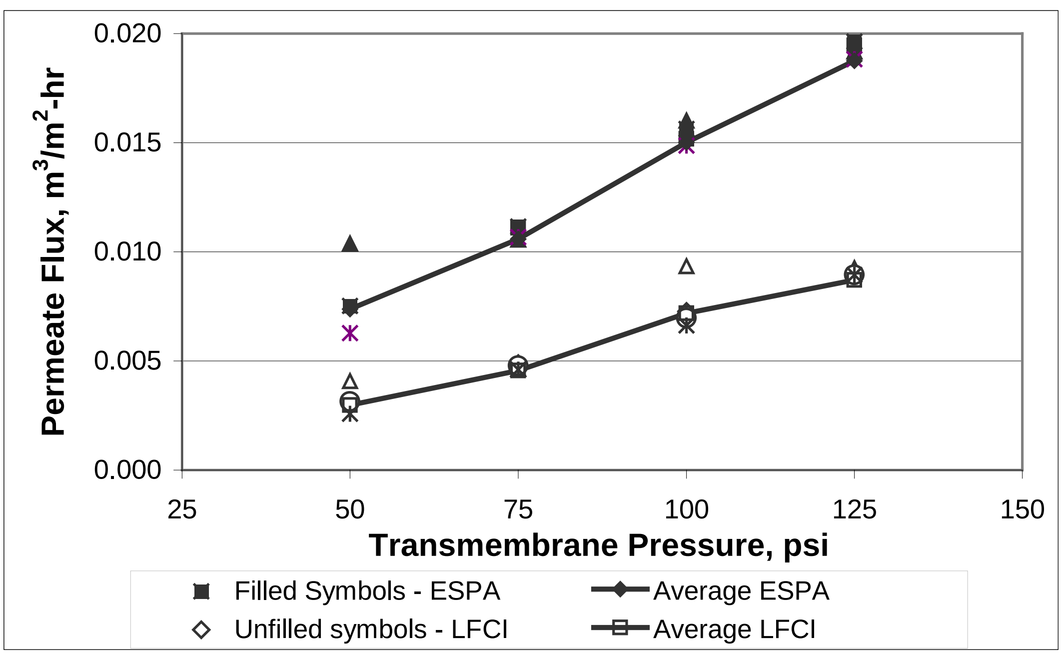

Figure 31. Permeate Flux versus TMP for Conventionally Treated Alamo River Water

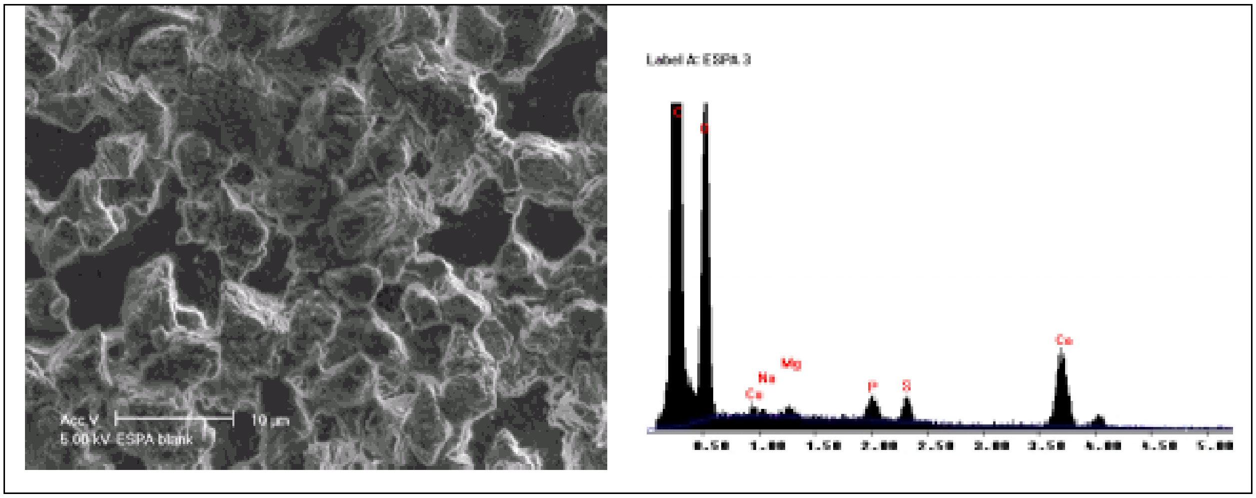

Figure 32. EDAX Quantification (Standardless) of Chemical Species Adsorbed to ESPA Membrane – Feed water CFMF

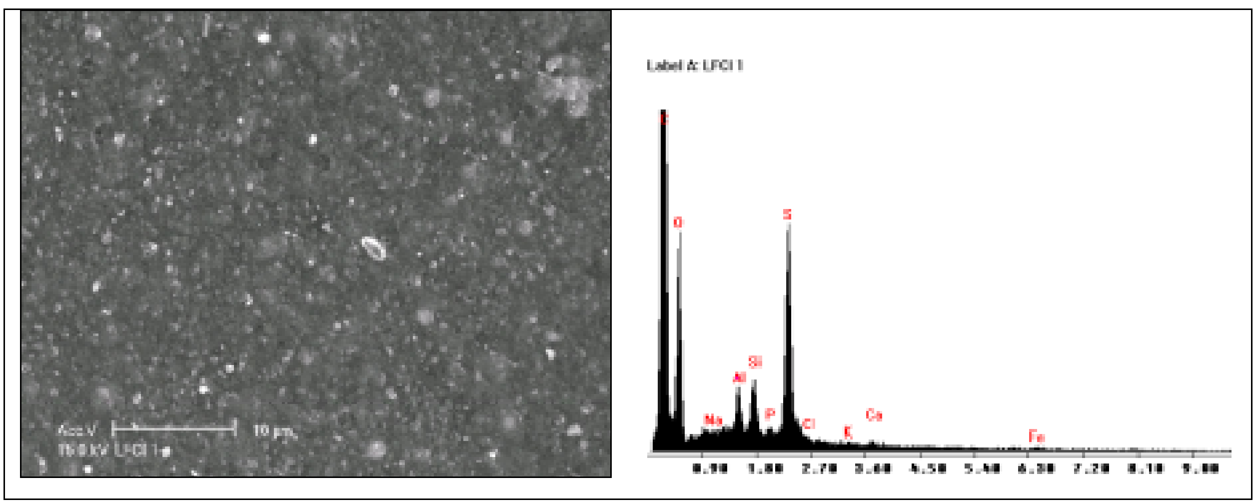

Figure 33. EDAX Quantification (Standardless) of Chemical Species Adsorbed to ESPA Membrane – Feed Water Conventional

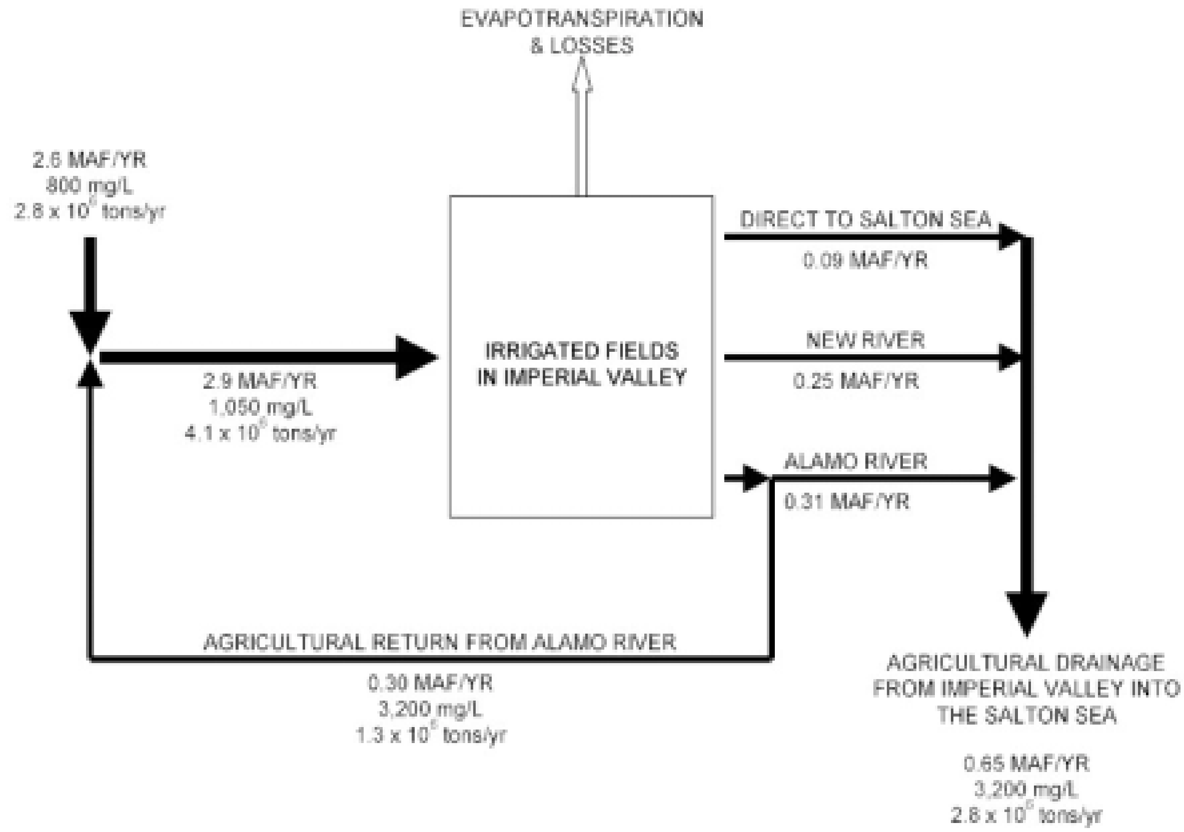

Figure 34. Alternative A Flow and Salt Mass Balance in the Imperial Valley

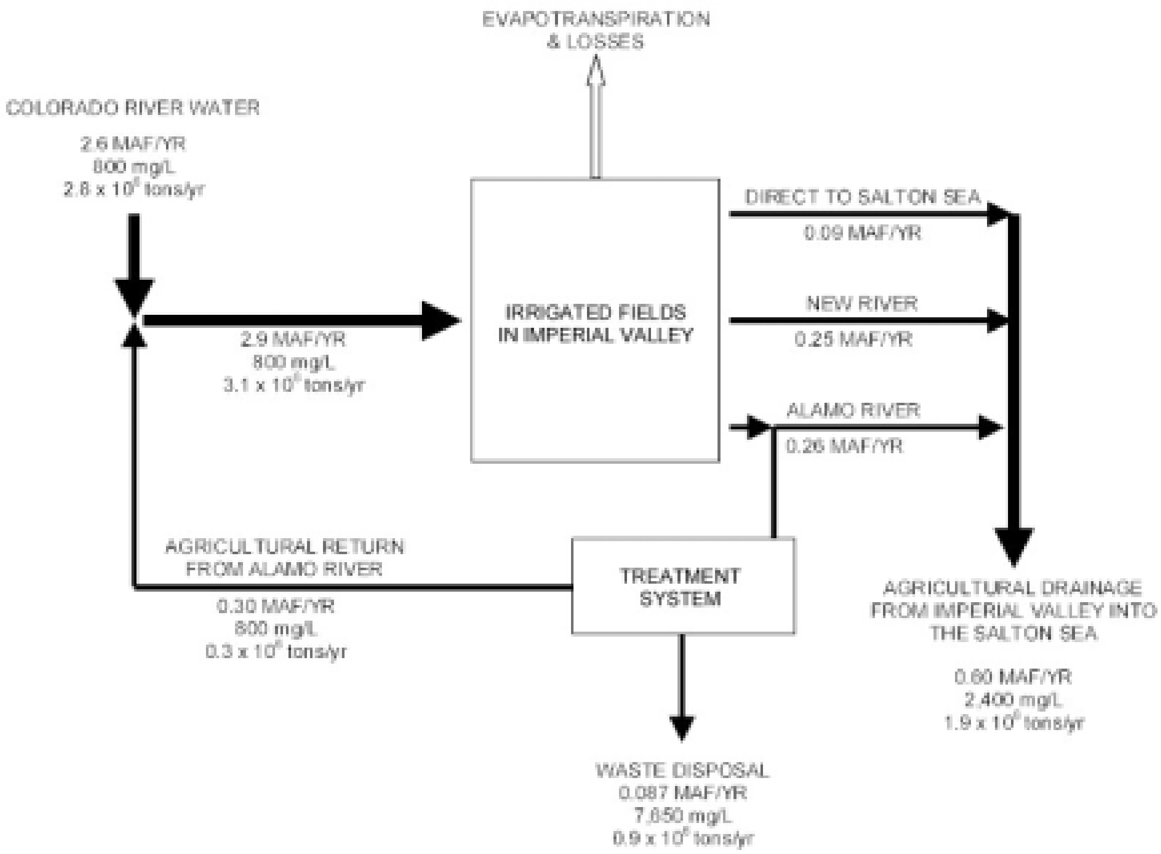

Figure 35. Alternative B Flow and Salt Mass Balance in the Imperial Valley

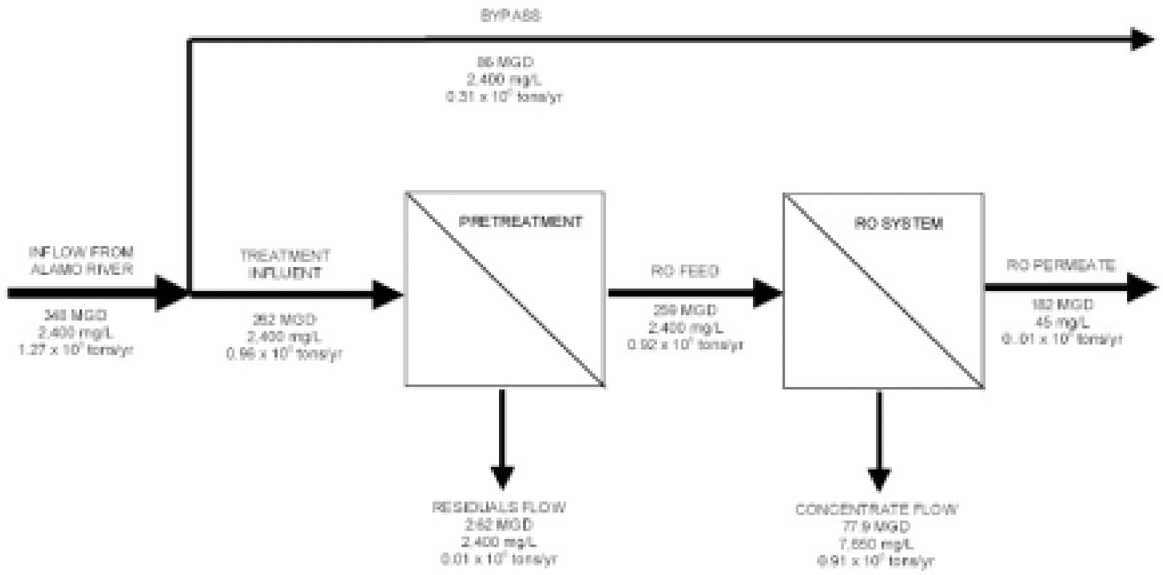

Figure 36. Alternative B RO System Flow and Salt Mass

APPENDIXES

Appendix A – Jar Test Procedures

Jar testing is a type of batch test used to simulate coagulation/flocculation/sedimentation (CFS) in water treatment. Jar tests are used to evaluate the relative effectiveness of chemical coagulants in promoting floc formation, and turbidity and suspended solids removal via sedimentation. Further, jar tests are useful in identifying optimum dosages for a particular chemical coagulant, optimum velocity gradients (G) for flocculation, and effects of temperature and pH.

Typical jar testing for this study consisted of three stages – chemical addition with mixing, staged flocculation, and sedimentation – which simulate rapid mixing, tapered flocculation, and clarification in a conventional continuous-flow water treatment plant.

For the PIER I project, the following coagulants and/or softening strategies were tested using jar testing: alum, ferric chloride, and selective calcium softening with ferric chloride. The procedural outline for a jar test is as follows.

1. Jars were each filled with 2L of test water.
2. Different doses of coagulant were added to each of the jars. Selected chemical dosages varied depending on coagulant type and results of previous jar tests. The range of doses for the jar test is presented in Table 31.
3. After coagulant addition., the stirrer was initiated at the highest possible rpm, approximately 300 rpm. The corresponding G value is 600 s^{-1} at 300 rpm. After one minute of rapid mix, the speed of the paddle mixer was reduced to the first rotational speed, which was selected on the basis of the selected G value. After 10 minutes, the paddle mixer was reduced to the second rotational speed. After another 10 minutes, the paddles mixer was reduced to the final rotational speed. Subsequent to the final 10-minute flocculation period, the paddle mixer was then stopped. The three G values and corresponding mixing speeds were based on the desired G value for the test. Summarized G values for each of the three flocculation stages are given in Table 32.
4. After the three flocculation periods, the suspension was allowed to settle for 60 minutes.
5. After the settling period, supernatant samples from each jar were collected for turbidity and pH. In the case where softening was conducted, hardness testing of the supernatant from the optimally dosed jar was conducted.
6. Optimum coagulant dose was selected subjectively on the basis of the lowest coagulant dose that resulted in the quasi-minimum turbidity.

Appendix B – CFS/DMF Operation

The bench-scale continuous-flow system used in this study consisted of two sequential unit operations. The first unit operation was designated as the CFS (coagulation, flocculation, sedimentation) system and was an integrated chemical mixing chamber, three-stage flocculator, and inclined-plate sedimentation tank apparatus. The design flow for the CFS system was 2 L/min, (0.5 gal/min). Specifications for the bench-scale CFS system are summarized in Table 33.

The second unit operation was dual-media filtration (DMF). Three parallel DMF units were employed to test different filtration rates. Specifications for the DMF units are presented in Table 34. The collective design flow for the three DMF units was 1 L/min.

For the PIER I project, the following coagulants and/or softening strategies were tested using bench-scale continuous-flow treatment systems: alum, ferric chloride, and selective calcium softening with ferric chloride. The procedural outlines for operation of the CFS and DMF units are as follows.

Coagulation/Flocculation/Sedimentation (CFS) System

1. The CFS unit was filled with settled Alamo River water from the previous experimental run. This was done so that the ionic strength of the CFS reactor, based on EC, was similar to the incoming raw water sample. (Differences in ionic strength affect density currents as well as particle stability.)
2. Once the CFS unit was filled, the rapid mix stirrer was initiated at 400 rpm, and the flocculator paddle mixers were adjusted to the appropriate rotational speeds, which depended upon whether softening was being tested. For coagulation only, the average G used was 40 s^{-1}. When softening was tested an average G of 60 s^{-1} was employed. Rotational speeds for the various stages are summarized in Table 35.
3. Once the rapid-mix and flocculator paddles were operated and calibrated, fresh raw Alamo River was pumped into the rapid mix chamber at a rate of 2 L/min.
4. The chemical feed pump, or pumps, was then initiated to provide proper coagulant/softening agent dosages. Coagulant dosage was based on jar testing results of the newly received Alamo River water. Softening chemical dosages were based on stoichiometric amounts of lime and soda ash for the average Alamo River calcium hardness reported by U.S.G.S. Selective calcium softening only was tested since calcium carbonate and/or calcium sulfate scale potential was the principal concern.
5. The effluent from the CFS for the first three hours of operation were not collected for subsequent treatment in the DMF units to allow the system to reach quasi-steady state. The CFS system has an overall detention time of about one hour. Thus, three hours represents three detention times.
6. Beginning at t = 3 hours, grab samples from the CFS taken every two hours for water quality analyses (Flow rate, TSS, EC, turbidity, pH, temperature, and particle size analysis). Flow rate adjustments were made if needed.

7. Also starting at t = 3 hours, CFS effluent was collected into an intermediate transfer tank to feed the DMF units. If softening was employed, 200L of CFS treated water was collected, pH adjusted to between pH 7 and pH 8, before initiated the feed to the DMF system. High pH water would most likely result in cementing of the DMF beds.
8. At approximately t = 9 hours, the CFS system was shut down and drained. Settled solids (sludge) were removed from the bottom of the CFS system through the underdrain.

Dual Media Filter (DMF) Units

1. Once sufficient CFS effluent was obtained, the three DMF feed pumps were initiated to start the filtration process. Flow rates were measured and pump speed were adjusted if necessary.
2. Grab samples and various operational measurements were made at t = 1, 4, 7, and 10 hours of the filter runs. Operational measurements included flow rate and water level above the media. Grab samples were analyzed for TSS, EC, turbidity, pH, and temperature).
3. Combining the effluent flows from the three DMF units and collecting 20L of effluent at each sampling time created a large composite sample that was used for particle size analysis and silt density index (SDI) analysis.
4. At the end of the filtration run, the filters were backwashed with tap water. During backwashing, each filter bed was expanded 75 percent and backwashed for 10 minutes. At the end of the backwash, the flow rate was decreased gradually to help ensure media separation (sand and anthracite).

Appendix C – Membrane Processes Operation

The bench-scale membrane unit processes used in this study were: 1) stirred cell membrane testing apparatus, 2) Continuous-Flow Re-Circulating MF/UF System (CFMF), and 3) Continuous-Flow RO Flat-Sheet Test Cell (RO). The unit operations were designed and constructed specifically for this project and can also be deployed to a field location for on-site investigations. Specifications for the bench-scale membrane systems are summarized in Tables 36-38.

Stirred Cell Membrane Testing Apparatus (SCT)

The feed water for SCT was either raw or settled-raw Alamo River water. If raw water is used, it is decanted using a peristaltic pump into the feed barrel the night before and stirred up using air immediately before being transferred to the pressurized feed tank. If settled raw water is used, the water is allowed to settle overnight in the collection barrel and decanted the morning of the experiment. In either case, the contents of the feed tank were continuously stirred using a magnetic stirrer plate during the experiment.

Specifications for the bench-scale stirred cell membrane apparatus are summarized in Table 36.

The operating procedures are:

1. Prepare test cell by first cleaning all tanks, tubing, and connectors. Cut membrane to fit the stirred-cell and rinse with warm tap water and place in the stirred-cell. Measure clean-water flux for pressures 10, 20, 30, 40, and 50 psi. Empty feed tanks and test cell.
2. Fill feed tank(s) with raw or settled-raw Alamo River water. Let all waters come to equilibrium (room) temperature, e.g. 21-23 C. Repeat pressure excursions such that steady state is attained for each pressure before proceeding to next.
3. Monitor the quality of the permeate visually during experiment and record flux throughout the experiment. Record turbidity at the end of the experiment.

Continuous-Flow Re-Circulating MF/UF System (CFMF)

The feed water for CFMF is either raw or settled-raw Alamo River water. If raw water is used, it is decanted using a peristaltic pump into the feed barrel the night before and stirred up using air immediately before connected to the pump. If settled raw water is used, the water is allowed to settle overnight in the collection barrel and decanted the morning of the experiment. Additional mixing was not required during experiment because of high flow rate during pumping

Specifications for the bench-scale Continuous-Flow Re-Circulating MF/UF System (CFMF) are summarized in Table 36 below.

The operating procedures are:

1. Connect feed tank containing selected feed water to the circulation pump. Place cooling coil in the feed tank and turn on cold-water tap. Monitor the temperature throughout the experiment.
2. Open all valves completely before starting pump to prevent membrane cartridge damage. Adjust valves to set pressure gradient along cartridge, TMP, and flow rate.
3. Beginning with lowest TMP measure flux every 15 minutes and repeat until steady state. Record flux and measure turbidity. Adjust valves and set unit to next TMP while maintaining pressure gradient and flow rate. Repeat for all TMP's.
4. At final TMP and steady state collect 2 L sample for water quality analysis (SDI, turbidity, TSS, EC)
5. End experiment by cleaning the membrane and backflushing system with cleaning solution followed by DI water. Perform clean water flux test and repeat cleaning procedure if warranted.

RO Continuous-Flow RO Flat-Sheet Test Cell (RO)

The feed water for RO is CFMF treated Alamo River water and Alamo River water treated by conventional treatment with dual-media filtration (DMF). Specifications for the scale flat-sheet test cell are summarized in Table 37.

The operating procedures are:

1. Each membrane is pre-conditioned prior to experiment. Cut flat-sheet membrane to size and soak in DI water, covered, for 3 hrs. Place membrane, shiny side down, in RO test cell and tighten bolts.
2. Place all discharge lines into feed tank containing 10 gallons of Nanopure water. Flush unit for 5 hrs at 200 psi and 0.16 gpm (center ball at 600 mark on flowmeter), making sure both sample ports are open with lines leading back into feed tank. Turn off RO pump leaving preconditioned membranes in RO test cell.
3. Connect feed lines to feed tank-containing feed (CFMF or conventional). Place the cooling coil in the feed tank and turn on cold-water tap. Monitor the temperature throughout the experiment. Open valves before starting pump to prevent membrane cartridge damage. Adjust valves to set TMP and flow rate.
4. Beginning with lowest TMP monitor flux until steady state. Record flux. Adjust valves and set unit to next TMP while maintaining flow rate. Repeat for all TMP's. At final TMP and steady state collect sample for water quality analysis and store membrane for SEM/EDAX analysis. Clean system by flushing with Nanopure water.